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THE UNIVERSITY OF ALBERTA

Removal of *Giardia lamblia* Sized Particles During Rapid Sand Filtration

by

David A. Kellendonk

©

A THESIS

SUBMITTED TO THE FACUCLTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Science

IN

Environmental Engineering

Department of Civil Engineering

EDMONTON, ALBERTA

SPRING, 1987

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Removal of Giardia lamblia Sized Particles During Rapid Sand Filtration submitted by David A. Kellendonk in partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering.

Supervisor

Daniel W. Smith

Date: April 10, 1987

ABSTRACT

Giardiasis is an intestinal disease transmitted by the cyst of the pathogenic protozoan Giardia lamblia and its occurrence in Canada is on the rise. In 1983, approximately 500 confirmed cases of this disease were reported in Edmonton within a six month period. Most of the cases were centered around the City of Edmonton's Rossdale water treatment plant. Waterborne transmission was suspected.

A bench scale water treatment pilot plant was constructed in order to quantitatively measure the performance of declining rate rapid sand filtration for the removal of Giardia lamblia sized cysts. Variables such as raw water characteristics, choice of pretreatment chemicals, water temperature, filter media and filter loading rate were modeled after the full scale E. L. Smith water treatment plant because this raw water was more difficult to treat than the warmer and more highly turbid raw water that enters the Rossdale water treatment plant. Polystyrene-divinyl-benzene latex spheres were successfully used as a cyst surrogate and a technique using epifluorescent microscopy was developed for collection and enumeration. This procedure allowed much higher recovery rates than found presently with live cysts. A potential for applying the cyst enumeration procedure to full scale facilities was demonstrated since spiking raw water with a cyst surrogate does not pose a danger to the public health.

The pilot scale testing showed that spheres in the 12 to 14 micron size range are more effectively removed than spheres in the 6 to 8 micron size range. Therefore larger cysts that are able to change shape due to the flexibility of their cell walls have an increased potential to escape capture in the filter. Low effluent turbidity and low particle count did not necessarily correlate with high sphere removals. A correlation was demonstrated between percent of particles removed in the Giardia cyst size range and percent of spheres removed in the filter. Finally, clarifier performance with respect to the removals of the spheres improved in proportion to the quantity of calcium hydroxide used in the lime softening process.

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1. INTRODUCTION

1.1 RESEARCH OBJECTIVES

In this study the experimental objectives were:

(a) To find a suitable model for Giardia lamblia that could reasonably approximate the behaviour of the cyst in a water treatment plant since using live cysts poses an unacceptable level of danger to the public health.

(b) To develop an effective recovery and enumeration technique for the cyst surrogate.

(c) To design and construct a lab-scale pilot water treatment plant for experimentation.

(d) To perform a series of runs employing varying doses of aluminum sulphate and calcium hydroxide and monitor the removal efficiencies of the surrogate.

(e) Measure the overall reduction of particles in the Giardia size range and compare these results with the removal efficiencies of the surrogate.

(f) To compare the removal efficiencies of the surrogate with the particle-size distribution results obtained from Coulter Counter analysis.

1.2 SCOPE

All testing was conducted on a bench scale water treatment plant apparatus that was designed and built for the project. On February 20, 1984 five thousand litres of raw sample water were collected from the North Saskatchewan River at E.L Smith Water Treatment Plant and were stored in 220

litre barrels inside a walk-in refrigerator during the testing period. Eleven runs in total were performed. The effects of making gross changes in the alum and lime doses on clarifier and filter effluent turbidity, on the removal of the Giardia surrogate, and on particle size distribution were examined. Variables such as water temperature, filter media composition, and filter loading rate were similar to the full scale operation of the E. L. Smith water treatment plant and were not changed during the course of the experiment.

2. LITERATURE REVIEW

2.1 GIARDIA AND GIARDIASIS

2.1.1 Taxonomy and Morphology

Giardia lamblia is a multi-flagellated protozoan belonging to the class: Zoomastigophora, order: Diplomonadida, and family: Hexamitidae (Barnes,1974). Its life cycle consists of a pathogenic reproductive trophozoite stage and a dormant cyst stage (Figure 1). Although the organism was previously known as Giardia intestinalis or Giardia enterica, it was not until 1915 that Charles Wadell Stiles in a letter to Koifoid and Christiansen (1915) established the commonly used name of Giardia lamblia.

The bilaterally symmetrical trophozoite is pear-shaped, having broad anterior end coming to a blunt point posteriorly. The dorsal surface is convex and the ventral surface is concave. Organism size ranges from 9 µm to 21 µm long, 5 µm to 15 µm wide and 2 µm to 4 µm thick. A distinctive sucking disc occupies most of the anterior ventral surface and is constructed of numerous parallal microtubules which lie adjacent to the ventral plasma (Sheffield,1979). Attachment to the host small intestinal membrane is accomplished by either contraction of the adhesive disk, or by attachment of the ventrolateral flange, or by the negative pressure produced by the movement of the

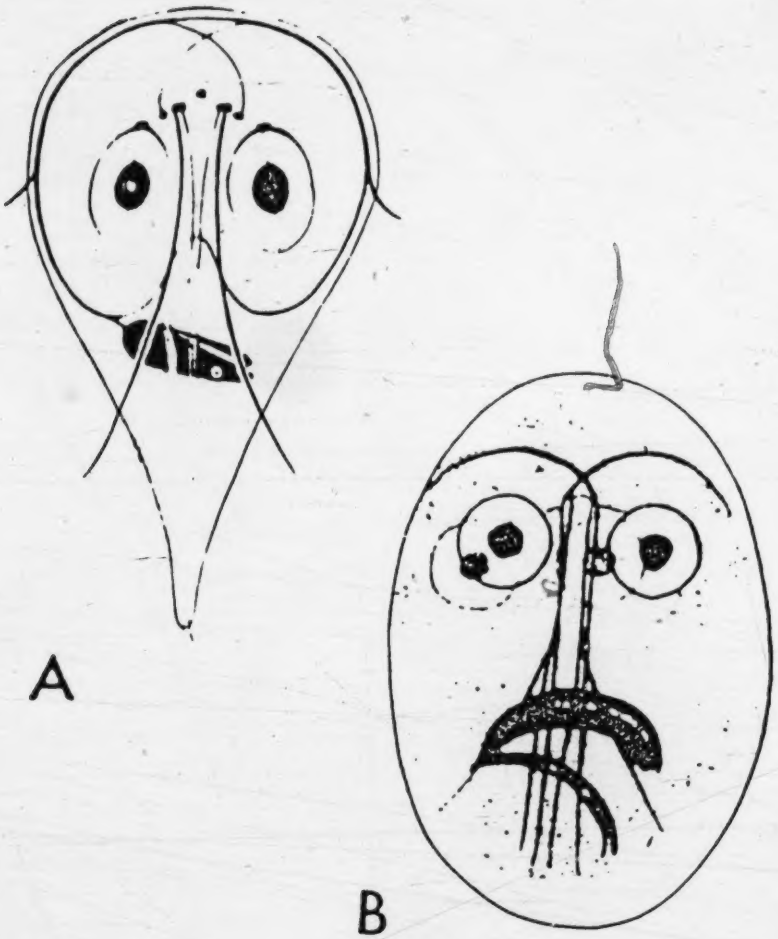


Figure 1. Giardia lamblia : Cyst and Trophozoite

(from Levine, 1979)

flagellae under the disk. The trophozoite reproduces by longitudinal binary fission (Levine,1979). Host to host transmission of the disease is accomplished via the cyst. Encystment of the trophozoite is triggered by some, as yet undefined, gastric event but is thought to be linked with its passage through the colon. A single diarrhetic stool may contain as many as 14 billion cysts and the stool of a moderately infected host can contain up to 300 million cysts (Porter, 1916 taken from Healy, 1979).

Cysts are ovoid to ellipsoid in shape and are smaller than the trophozoites having a length of 8 µm to 12 µm and a diameter of 7 µm to 10 µm (Sheffield,1979). The flagellae of the trophozoite are lost or reabsorbed during encystment, however researchers have observed their neurological remnants and also fragments of the sucking disc within the cyst. The surface of all cysts of the Giardia species is smooth and without a consistent pattern of pits, pores, or major depressions. It also lacks ridges, projections, and a consistent pattern of granularity and roughness (Toombs, 1979). Electron microscopy shows the external wall to be composed of thin fiberous elements interspersed with fine particles (Sheffield,1979) which appear to impede the invasion of large molecules. A thin membrane on the inner wall seems to restrict the passage of small molecules. Combined, these form a resilient, but flexible shell which effectively isolates the organism from an external hostile environment and according to Logsdon and Lippy (1984) makes them more resistent to disinfection than most other microbial

pathogenic agents.

The cyst is also suspected of having reproductive capabilities, possibly binary fission, however the process has not as yet been witnessed. Young cysts have two nucleii while mature cysts develop four nuclei. During excystation two dual nuclei trophozoites are produced from a single cyst thus completing the cycle.

2.1.2 The Disease: Symptoms and Treatment

The intestinal disease caused by the protozoan parasite Giardia lamblia is termed giardiasis. Disease transmission is via the cyst and travels the fecal-oral route. Rendtorff (1979), in an experiment conducted on adult male volunteers, determined that the minimum number of swallowed cysts that was required to infect a new host was between one and ten.

Although some live trophozoites may escape into the feces, they are unable to survive outside the body for more than 24 hours. Any that might be subsequently ingested could not further survive the acidic gastric environment of the new host. The well protected cyst however is able to reach the small intestine where conditions are amenable to support immediate excystment and the emergence of daughter trophozoites. A dense layer of parasitic and motile trophozoites rapidly colonize the intestinal epithelium where instead of lysing the host cells, they feed on its mucous secretions. The ability of the host cell to absorb fats and nutrients is thus impeded and this can trigger the onset of

the disease. The symptoms can manifest themselves 7 to 21 days after exposure. Table 1 (Shearer,1984) outlines the various symptoms associated with the different stages of the disease. Researchers have also noted infection of the gall bladder which can lead to jaundice and colic. Other symptoms that are coincidentally associated with Giardia lamblia are urticaria (swelling and redness due to an allergic reaction), erythema multiforme (swelling due to capillary congestion), and arthritis Wolfe,1979).

Many individuals with giardiasis are asymptomatic (possibly up to 75%) when diagnosed and may never actually exhibit the symptoms. A greater number of asymptomatic carriers are now being identified by physicians who routinely administer Giardia diagnostic tests in epidemic areas. Asymptomatic carriers create special problems in that they can freely infect any population with whom they come into contact (Black, 1977). This is especially true of children who experience a high degree of touching during play. In asymtomatic carriers little information is available as to the degree of cyst viablity, the duration of cyst passage, or whether symptomatic or asymptomatic giardiasis is transmitted.

After a few days to several months the trophozoite disappears spontaneously from the gut of the host. The reasons and the mechanisms are not yet completely understood. There appears to be some early research data which supports the development of an immunity to future infections in mice. However, the process for development of antibodies in humans

Table 1

Symptoms Associated With Different Stages of Giardiasis

(from Shearer, 1984)

Stages		
Acute	Subacute	Chronic
Sudden diarrhea with explosive, watery, often foul-smelling stools.	Intermittant attacks of soft foul-smelling stools.	Periodic, brief episodes of loose semi-solid foul-smelling stools, with constipation occasionally occurring between attacks.
Marked flatulance and abdominal distention.	Greater-than-normal flatulance, abdominal distension.	Passage of foul smelling flatus.
Abdominal cramps, often mid-epigastric.	Mid-epigastric or more generalized abdominal pain.	Abdominal distention.
Nausea, loss of appetite occasional vomiting.	Belching of foul-smelling gas.	Some weight loss.
Chills low-grade fever, headache.	Fatigue, lassitude, malaise.	Intermittent attacks of lassitude and malaise.
Belching.	Fatigue, lassitude, malaise.	
Generalized weakness.	Hives (few cases).	

has not been identified. In addition, the degree of any acquired immunity may vary from being temporary to permanent in nature.

Wolfe (1979) reports that the treatment of choice for giardiasis is quinacrine hydrochloride (Atabrine). Recovery rates of 95% to 100% have been reported. Side effects include dizziness, headaches, gastrointestinal upset, jaundice and toxic psychosis. He states that metronidazole (Flagyl) is an alternative and is almost as effective. Side effects including dizziness, headaches and gastrointestinal disorders. Rash and changes in blood cell count have been observed. In addition, this drug has not been recognized by the U.S. Food and Drug Administration since it has been shown to be carcinogenic in rats and mutagenic in bacteria. Furazolidone is used as an alternative to quinacrine and has a cure rate of about 77%. Since it can be administered in liquid form it is useful for the treatment of children. Side effects include drug allergy reactions such as hemolysis, hypotension, urticaria, vomiting diarrhea and nausea (Wolfe, 1979).

2.1.3 Prevalance, Transmission and Detection

Schultz (1977) estimates that between 3% and 7% of the adult (U.S.) population harbour the Giardia lamblia parasite, thus making it the most common intestinal pathogenic parasite in the United States (Center for Disease Control, 1977). Shearer (1984) states that because of the inaccuracy of our diagnostic tools, the true prevalance

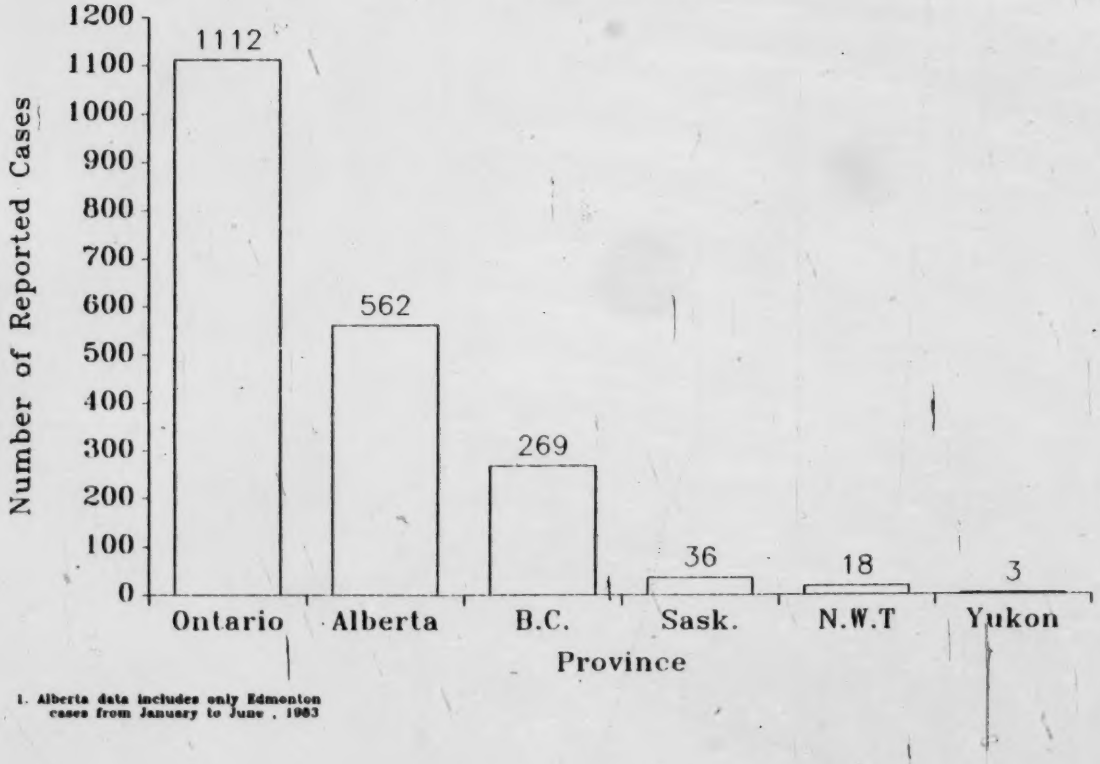
cannot be known and may range from between 1% and 35% depending on the area and the population studied. Prevalance of the disease is consistently high among people unable to practice adequate levels of hygiene. In the U.S., Shearer estimates that the number of people infected is between 2% and 15% of the entire population.

Endemic areas are located primarily in the north eastern United States from Pennsylvania to New Hamphire, and in the Rocky Mountains and Pacific Coast States (Lippy and Logsdon,1984). In Canada, recent outbreaks have been documented in Ontario, Alberta (Jorgenson, 1983), and British Columbia (Bryck and Walker,1984). The results of a 1983 Canadian survey (from Canada Disease Weekly Report, 9-30) are shown in Figure 2. In many of these areas, waterborne transmission is suspected because drinking water is drawn from contaminated mountain source streams. When the natural water is of good quality and there is an absence of point source wastewater discharge, many municipal systems provide minimal treatment; often only chlorination. Over eighty outbreaks of waterborne giardiasis have been reported in the United States and Canada between 1965 and 1985. Figure 3 shows that the number of outbreaks is on the rise. However, more sophisticated laboratory detection techniques coupled with well publicized outbreaks which have heightened public awareness have also contributed to an increase in the reporting of infections.

In many mountain lakes the winter water temperature is 0^{o} C. to 3^{o} C. and a cyst can remain viable for many months.

Figure 2 Giardiasis in Canada

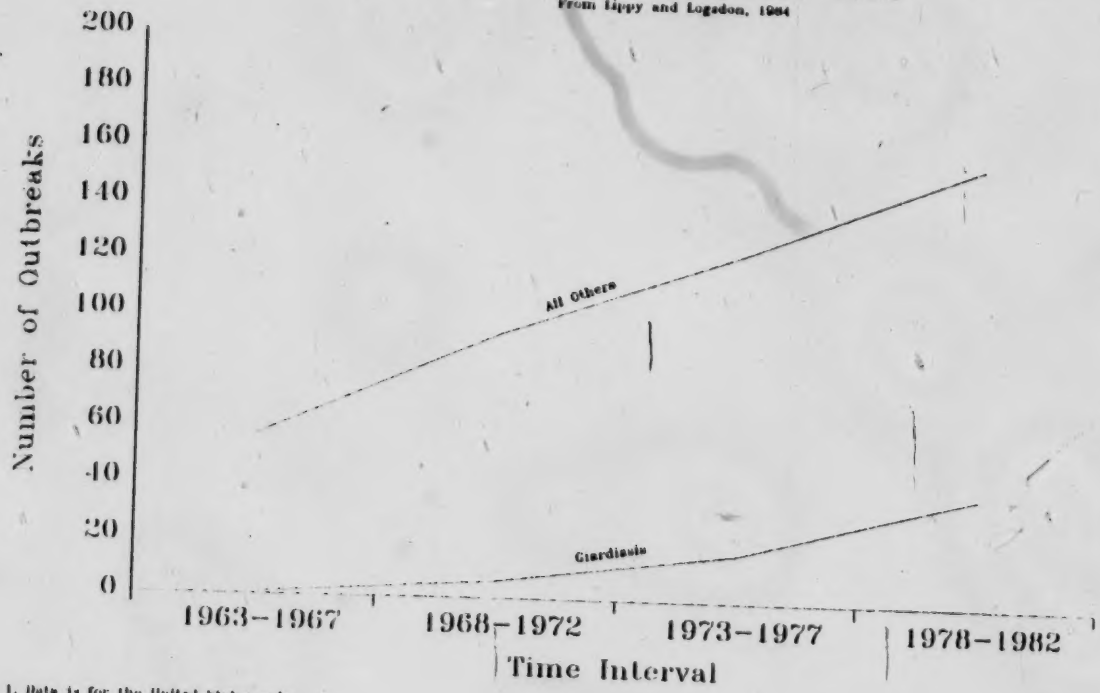
From Canada Weekly Diseases Report
Volume 9-30 (1983a)



1. Alberta data includes only Edmonton cases from January to June , 1983

Figure No.3 Waterborne Giardiasis Outbreaks 1963–1982

From Lippy and Logsdon, 1984



1. Data is for the United States only

Rentdorff and Holt (1964) found infective cysts after sixteen days of storage at 8° C. Davies and Hibler (1979) successfully infected dogs with human cysts that had been refrigerated for twenty-one days. Boeck (1921) found some cysts to be viable after 32 days when stored in distilled water at 12°C. to 32°C. and at least 66 days when stored in water under a cover slip on a slide. Evidence suggests that repeated freezing and thawing is more detrimental to cyst survivability than prolonged exposure to the cold. Therefore a potential exists for cysts to collect during the winter months resulting in a health hazard that can become a threat during spring break-up when an accumulation may be washed downstream.

Davies and Hibler (1979) investigated the possibility of cross-species transmission of giardiasis. They concluded that six species of mammals (i.e. beavers, cows, cats, dogs, coyotes, and humans) were all potential hosts to Giardia lamblia. They gave human source cysts to rats, gerbils, guinea pigs, dogs, racoons, bighorn sheep, pronghorn antelope and mule deer. Each of these subsequently became infected. Their research strongly supports the likelihood of cross-transmission between some mammalian species and humans. Therefore an increase in the simultaneous use of mountain and wilderness areas by man and these animals will escalate the danger of infection to humans. Drinking water from a crystal clear mountain stream is not safe since it might well be contaminated. The risk of cross-transmission is heightened by people who ignore this danger.

Prior to 1965, giardiasis was erroneously considered to be a disease affecting only children and transmitted solely by direct contact. Since most of the reported cases occurred in kindergartens and day care centers, it was often overlooked and misdiagnosed in adults. Although surface water systems are an important consideration in the transmission of the disease, person-to-person contact is also significant and should always be investigated when giardiasis is diagnosed.

Detection of the disease at the clinical level is improving. The most common and least expensive test, repeated fecal smears, if performed one to three days apart has an accuracy of between 30% to 100%. A more reliable method, counter-immunoelectrophoresis (CIE), is reported to be over ninety percent accurate in detection of Giardia from just a single stool specimen. Immunofluorescence is currently undergoing testing in order to determine its diagnostic usefulness (Riggs,1984). Serological testing although useful for epidemiological purposes is not yet accurate enough for diagnosis in acute cases. Other tests that are gaining in acceptance are examination of the duodenal fluids (90% to 100% effective) and small bowel biopsies (60% to 100% effective). Once these new methods become cost effective and more generally available, the reported cases of giardiasis might well reach unprecedented levels.

2.1.4 Giardiasis Outbreaks and Water Treatment

Incidents of waterborne giardiasis are most often caused by mechanical failure, operator error, or inadequate plant

design; all of which result in poorly treated drinking water. The first reported outbreak of waterborne giardiasis occurred in Aspen, Colorado in 1965 (Moore, 1969) where there were twenty-three confirmed cases of the disease. Raw drinking water was taken from deep wells and chlorination was the only treatment applied. A cross-connection between the well and a sewer main was discovered to be responsible for the contamination. Chlorination alone did not provide adequate protection.

During an eight month epidemic in Rome, New York in 1975-1976, researchers collected cysts which had passed through the water treatment system. Cyst viability was tested by in-vitro injection into dogs. Epidemiological surveys counted 350 confirmed cases while between 4800 and 5300 were suspected (Shaw, 1977). Treatment consisted of only a chloramination unit and it was concluded that inadequate disinfection during periods of high demand or plant operation failure facilitated cyst breakthrough.

In Camas, Washington in 1975, 25 cases of giardiasis were reported and another 600 unconfirmed infections were suspected. This outbreak was significant in that it was the first time in which a water supply that was both filtered and disinfected allowed the passage of cysts (Kirner, 1978). An investigation revealed that infected beavers living upstream were a possible reservoir and source of the contamination. An inspection of the water treatment plant revealed that there was a cross-connection between the raw water intake and the coagulant feed line. In addition, some short circuiting

within the filter bed was observed. The effectiveness of coagulation was questioned because there was insufficient control over the coagulant feed rate and an unusually short detention time prior to filtration. A subsequent analysis using a particle counter indicated only a 25% removal of particles in the Giardia lamblia size range. Lastly, investigators demonstrated a strong correlation between the breakdown of an automatic chlorinator and the majority, but not all of the infections.

In Berlin, New Hampshire in 1977, within a two week period, 100 cases of giardiasis were confirmed and approximately 3450 more were suspected (Lippy,1978). Again, inadequacies in plant operation such as the formation of filter mud balls coupled with inadequate chlorine doses and contact times were believed to have contributed to the outbreak. More importantly, there appeared to be a structural failure in the backwash channel and this allowed some short circuiting to the filtered water so that cross-contamination was likely.

In Edmonton, Alberta about 500 cases of confirmed giardiasis were reported in a two month interval starting January, 1983. Figure 4 (from Canada Diseases Weekly Report, 9-48) summarizes the epidemiological information. The actual number of infections was thought to be much higher (i.e. 7 to 10 times) because only symptomatic cases were diagnosed and only those individuals who sought medical help because of the severity of their illness were counted. The report notes that there was an unusual and unexplained clustering of cases

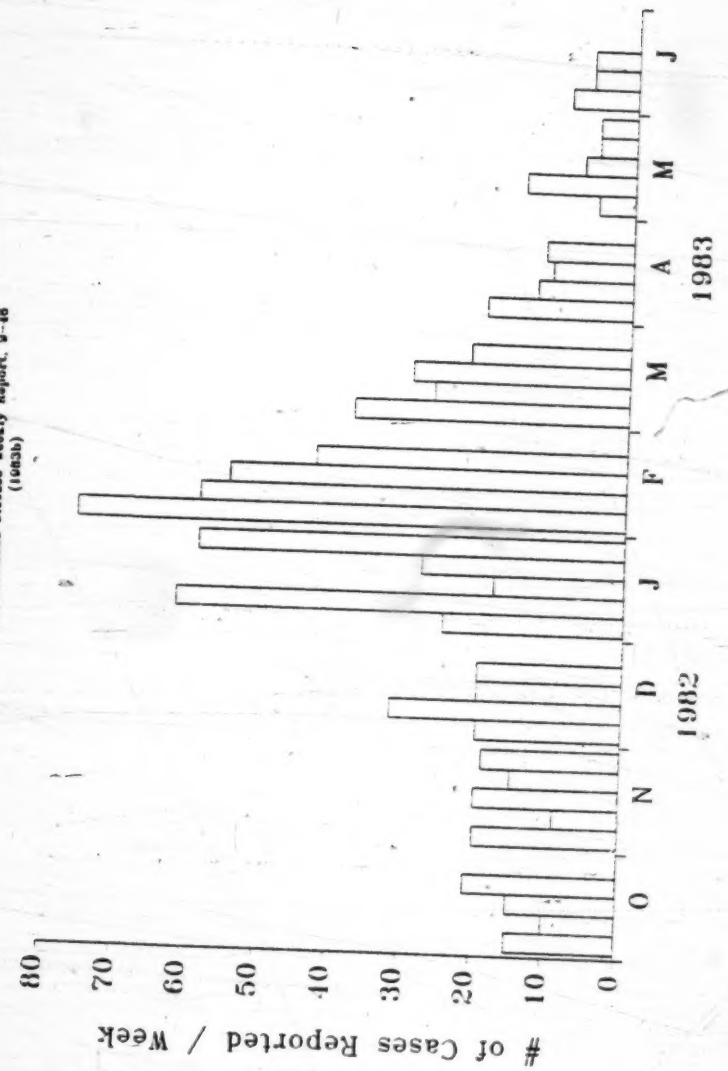


Figure 4 Edmonton Giardiasis Outbreak

From Canada Disease Weekly Report, 9-46 (1983b)

around Rossdale, one of the major water treatment plants. Logsdon in 1986, suggested a similarity between turbidity removals and cyst removals and stated that if 90% of the turbidity could be achieved in each of the three solids separation steps at Rossdale, then an overall removal efficiency of 99.2% to 99.9% cysts would be possible. After an April, 1986 site inspection of Rossdale however, Logsdon lowered his original estimate. The raw water winter conditions of low turbidity and near freezing temperatures made alum treatment difficult and laboratory analyses showed that turbidity reductions in the alum clarification stage could vary from 0% to 90%. As well, Rossdale used a low pH lime softening process that produced non-gelatinous floc which might be less effective in cyst removal in the clarifier than what could be acheived with high pH lime softening.

Logsdon also commented on a report by Collier and MacDonald (1983) and suggested that in light of the relatively low oxidation potential of chloramine, the decreasing incidence of giadiasis with increasing distance from Rossdale was consistent with the longer contact time provided within the distribution system.

Table 2 from Logsdon and Lippy (1984) provides a general summary of noted deficiencies in public water treatment systems that are related to giardiasis outbreaks. The primary cause appears to be inadequate treatment or equipment failure which allows the passage of some untreated water into the potable supply. Table 3 from Logsdon and Lippy

Table 2

Deficiencies Associated With Giardiasis Outbreaks

In Public Water Systems, 1963 to 1982

(from Logsdon and Lippy, 1984)

Catagory of Deficiency	Percentage
Inadequate treatment or equipment failure	66.7%
Use of untreated groundwater	12.3%
Use of untreated surface water	10.5%
Deficiencies in the distribuion network	5.3%
Miscellaneous or unknown	5.3%

Table 3

Outbreaks in Public Water Systems, 1963 to 1982

(from Logsdon and Lippy, 1984)

Problem	Number of Times Noted
Chlorination inoperative	3
Chlorination inadequate	13
Chlorination adequacy unknown	14
Coagulation deficient	5
Filtration deficient	4

(1984) shows that the majority of treatment failures with respect to giardiasis outbreaks can first be traced to problems with disinfection. The next most significant cause was a failure in coagulation and this was followed by filtration problems. This data clearly underlines the importance of a multiple barrier approach to the treatment of Giardia infected water because no single step can be expected to be 100% efficient.

The effectiveness of free chlorine for disinfection was studied by Jarroll et al., (1981), and Olson (1982). Excystation ability of cysts in gerbils was used as the criterion of viability. Jarroll confirmed experimentally that a decrease in water temperature, and an increase of pH from 6 to 8 reduced the oxidant effectiveness. This finding is consistent with the chemistry of chlorine.

When chlorine gas is dissolved in water the chemical reaction favours the production of hypochlorous acid (HOCL) at all water temperatures. HOCL is a weak acid and undergoes the following partial dissociation.

$$HOCL \rightleftharpoons H^+ + OCL^-$$

The degree of dissociation depends primarily on pH and to a lesser extent on temperature. At pHs below 6 almost all of the acid is in the undissociated form (HOCL) and at pHs of 9 or greater almost all of the acid is ionized to the hypochlorite ion (OCL^-). Friedman (1983) states that since hypochlorous acid is a small and electrically neutral molecule, it is readily able to pass through the cell walls and into the cell body where it then oxidizes critical

enzymes and kills by disruption of the cell's normal metabolism. Hypochlorite ion, by contrast has a negative charge is unable to diffuse through the similarily charged cell walls with the same facility as HOCL and is therefore less effective as a disinfectant.

A decrease in temperature reduces the ionization potential of the acid thus driving the equilibrium reaction to the production of more OCL^-. Weber (1972) states that for every drop of 10° C. in water temperature, the rate of most chemical reactions decrease by one-half. Lower water temperatures should require a corresponding increase in contact time in order to achieve the same kill rate.

The high residual chlorine concentrations used in the Jarroll et al. (1981) experiment (i.e. 1.5mg/L to 4.0 mg/L) are not normally used in full-scale systems because of the need to avoid the generation of chlorinated organic by-products. However, the results are useful because he shows that longer contact times can compensate for lower disinfection doses.

Olson showed that free chlorine was more effective at a pH of 6.5 than 7.5 thus a shorter contact time was needed in order to acheive a 100% kill of the cysts. He determined that with a 0.2 mg/L residual, a contact time of between 12 and 18 hours was required to inactivate all of the cysts. A 1.0 mg/L residual required a contact time of between 3 and 4 hours to have the same effect.

Hoff et al. (1984), in a study using chlorine and ozone, compared the resistances of Giardia lamblia to other

drinking water pathogens. They found that although cyst resistances were approximately one order of magnitude higher than poliovirus I and two to three orders of magnitude higher than E.coli., they could be inactivated by these two drinking water disinfectants under well controlled treatment plant conditions.

2.2. REVIEW OF COAGULATION AND FILTRATION

2.2.1 Coagulation

Many impurities are too small for gravitational settling alone to be an effective removal process, therefore the aggregation of fine particles into larger, more settleable aggregates is essential for effective sedimentation. This two-step process is called coagulation and consists of a flocculation or particle-transport step followed by particle destabilization when contact occurs.

Interparticle contact can be accomplished in several ways (Weber,1972):

(a) contacts by thermal motion or Brownian diffusion.

(b) contacts resulting from bulk fluid motion or transport achieved by stirring.

(c) contacts resulting from differential settling when a faster settling particle overtakes and collides with a slower settling particle.

The four methods of destabilization are (Weber,1972):

(a) compression of the diffuse layer.

(b) adsorption to produce charge neutralization.

(c) enmeshment in a precipitate.

(d) interparticle bridging.

Destabilization by compression of the diffuse layer is accomplished by the introduction of oppositely charged ions (i.e. counter-ions) into an aqueous colloid suspension. As counter-ions are added, the natural electrostatic repulsion of the like-charged colloids is decreased with the result that the thickness of the diffuse layer and the interparticle separation required to maintain electroneutrality is reduced. When the net repulsive force or the activation energy barrier is overcome, van de Waals forces of attraction take over to promote particle aggregation.

The ability of a coagulant to destabilize a colloidal suspension by charge neutralization is a combination of the coagulant-colloid, coagulant-solvent, and colloid-solvent interaction. Tamamoshi and Tamaki (1959) demonstrated that the colloid-coagulant interactions could be even more important than the coulombic effects. In their work with dodecyclammonium ions they found that this long-chain amine was able to adsorb onto the surface of a colloid when there was low coagulant-solvent interaction. Destabilization resulted when enough covalent bonding sites were occupied so that the net electric repulsive charge on the particles was diminished to the point where aggregation could take place. Restabilization was possible when excess ions were adsorbed thus reversing the total net colloidal charge in the suspension.

When a metal salt such as $Al_2(SO_4)_3$ or a metal oxide such as $Ca(OH)_2$ is used as a coagulant in a concentration high enough to cause rapid precipitation of a metal hydroxide

(i.e. $Al(OH)_3$) or a metal carbonate (i.e. $CaCO_3$) colloid particles can be enmeshed during settling (Packham, 1965). If the pH of the solution is in the neutral or acid range, reaction kinetics favour an increased rate of precipitation in the presence of anions such as SO_4^{-2}. The colloid particles also serve as nuclei for the formation of floc so that the rate of precipitation increases in relation to the colloid concentration.

Interparticle bridging is accomplished with synthetic polymers having chemical groups that can interact with bonding sites on the surface of the colloids. One of these groups can adsorb to the particle surface leaving the rest of the long chain polymer extending into the solution. The chain has many sites onto which other colloids attach thus producing a colloid-polymer-colloid bridge. Eventually, enough particles are joined so that a settleable floc is formed. Restabilization becomes a factor when the colloid concentration is so low or the polymer concentration is so high that all available colloids are bound. The loose end of the polymeric chain may then wrap around the original particle so that no further bridging can take place.

Conventional coagulation processes in Alberta typically use enough aluminum sulphate so as to exceed the solubility limit of its hydroxyl complexes. Destabilization may be brought about by enmeshment in a sweep floc or by Al(III) polymers which are formed as intermediate species in the precipitation of the metal hydroxide. Hydroxyl metal complexes are adsorbed on to the colloidal particles

resulting in destabilization by charge neutralization. The quantity of Al(III) required to bring about destabilization depends on colloid concentration and pH. The isoelectric point of the metal hydroxide is at a pH of 6.1 . Above this, anionic polymers predominate and adsorption of negatively charged polymers by negatively charged colloids does not occur so that destabilization by charge neutralization is not a factor (O'Melia and Stumm, 1967. Hahn and Stumm, 1968).

Cold and low turbidity waters are generally difficult to treat with alum salts. Waters with low suspended solids concentrations and high alkalinity require high alum doses and coagulation is accomplished by enmeshment in a sweep floc. Alternatively, a coagulant aid may be used to increase the rate of interparticle contact and promote destabilization by adsorption and charge neutralization, thus reducing the quantity of alum needed for effective coagulation.

Treating low suspended solid and low alkalinity water can be aided by the addition of extra colloids (i.e. bentonite clay), to increase the potential for contact or by increasing the alkalinity (i.e. soda ash) to promote a more rapid formation of sweep floc; or both. The use of alum alone may be ineffective if the natural alkalinity of the water is low since its addition would reduce the pH and this would chemically inhibit the rapid formation of a sweep floc. A similar result would occur in water having a higher pH (i.e. greater than a pH of 8) and higher alkalinity. Floc formation would be retarded and more alum would remain in solution because aluminum is more soluble in water at a

higher pH. Destabilization by charge neutralization is not usually an adequate removal mechanism since the rate of interparticle contact between the colloids remains low.

2.2.2 Filtration

Water filtration theory indicates that organisms of the size of Giardia lamblia cysts should be removed by conventional rapid sand filters provided that proper attention is given to particle transport and attachment within the filter medium. These mechanisms are very complicated and depend on the physical and chemical characteristics of the filter media, the rate of filtration and the chemical characteristics of the water. There is disagreement in the literature as to the relative importance of each of these processes.

The physical forces responsible for particle transport may include gravity settling, diffusion, direct interception or hydrodynamics. These are affected by such physical factors as media size, filtration rate, water temperature, and the density and size of the suspended particles. Herzig et al. (1970), showed that gravity settling was the dominant transport mechanism for particles greater than 25 microns. Yao et al. (1970) using a model in which a granular filter bed was the collector, proposed an analogy between transport in filtration and that of flocculation. They discovered that particles in the one micron size range had the least opportunity to approach the grains of a filter bed. For particles smaller than one micron, removal efficiency

increased with decreasing particle size and for particles greater than one micron removal efficiency rapidly increased with increasing particle size. Yao et al. (1970) concluded that Brownian diffusion became a more important transport mechanism with decreasing particle size. Conversely, interception along stream lines and gravity settling became the dominant transport mechanisms as the particles increased in size. Boyd and Ghosh (1974) having found no variation in the percent removals of 3.7 micron to 7.0 micron sized particles, concluded that the mechanism of transport and removal in this size range did not change and therefore removals in this size range should be the same.

In a second experiment, Ghosh et al. (1975) determined that in a clean bed for particles larger than one micron, double-layer forces of attachment play a very minor role in particle capture. For smaller particles, he observed that as negative zeta potentials decreased, the effectiveness of particle capture increased for the whole range of particle sizes studied (i.e. 0.091 μm to 1.101 μm). For particles less than one micron, Ghosh concluded that theoretical models in which Brownian diffusion is included best described the experimental data.

However, O'Melia (1967) concluded that the importance of the different transport mechanisms was insignificant in filter design. He suggested that all particle transport in filter pores was very efficient and that by applying the correct chemical pre-treatment, the whole range of particles from 0.01 microns to 100 microns

could be effectively filtered. Adin et al. (1979) noted that, for many years, clay and bacteria had been effectively filtered from water even though a large portion of the particles are in the 1 micron size range. They suggested that filter control efforts would be made more effective and easier to understand if attachment was viewed as the major factor in the filtration process.

Once a suspended particle has approached the surface of the filter media an attachment mechanism is required to retain it. The two models most often cited are:

The classic "double-layer" model is based on electrostatic repulsive forces and van de Waal's attractive forces (O'Melia and Stumm, 1967).

Although individual hydrophobic colloids have an electrical charge, a colloid dispersion in water does not have a net overall charge. For electroneutrality to exist, the charge on the colloidal particle must be counter-balanced by an accumulation of ions of the opposite charge (counter-ions) in an area immediately surrounding the particle. The ions involved in this electroneutrality are arranged in such a way as to constitute the so-called electrical double-layer, which is composed of an inner dense layer of counter-ions called the Stern layer separated from an outer, more electrically diffuse, Gouy layer by a plane of shear (Figure 5). The electrical charge measured at the location of this plane of shear has been termed the zeta potential. When negatively charged colloids approach the similarly charged media their diffuse counter-ion atmospheres

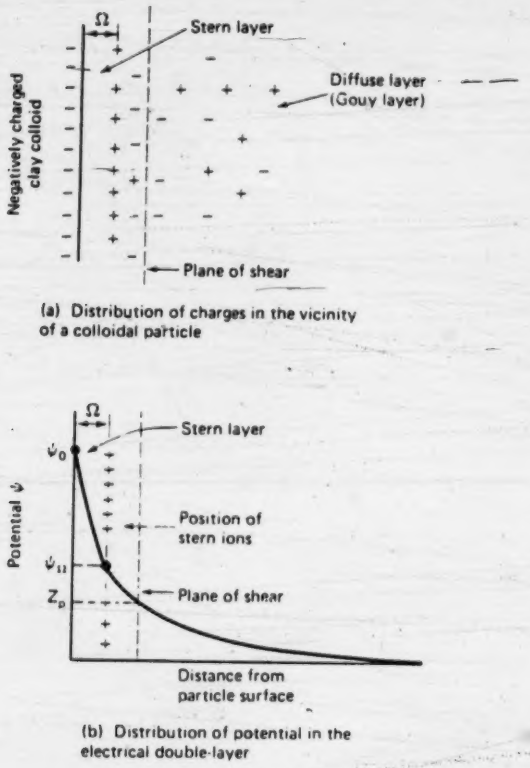


Figure 5 Stern's Model for the Electrical Double Layer

(after Van Olphen, 1977)

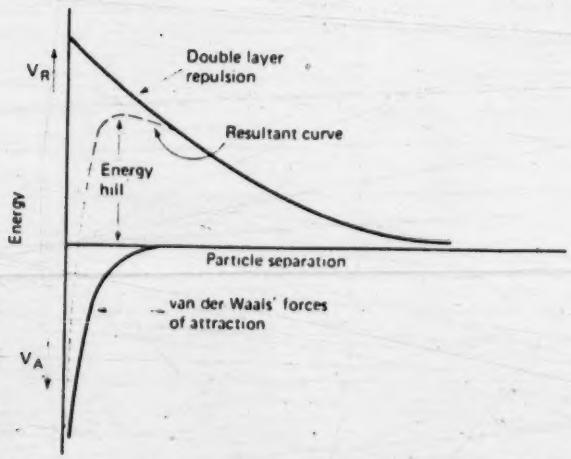


Figure 6 Repulsive and Attractive Energies as a Function of Particle Separation (after Van Olphen, 1977)

begin to interact and cause the colloids to be repulsed. The magnitude of repulsion decreases exponentially with increasing particle separation. Stability is maintained when these repulsive forces are counterbalanced by the inter-molecular van de Waal's forces of attraction. The repulsion and attractive forces can be represented by curves (Figure 6) which show that at a certain distance of separation, repulsive forces predominate. However, if these particles can be brought close enough together the van de Waal's attractive forces dominate and the colloid is then able to attach itself to the media. When this repulsion-attraction mechanism applies, different chemical factors (i.e. counter-ionic strength and pH) can affect the attachment process by either increasing or decreasing the repulsive potential. In general, any process that is able to decrease the zeta potential between the particle and the media increases the possibility of attachment.

The "bridging model" is used to explain the attachment which results when a flocculant is used to produce chemical bonding and bridging between a suspended particle and the media. Most modern filtration theories depend at least partially on this model.

Stumm and Morgan (1962) showed that the action of conventional flocculants is primarily due to their hydrolysates and takes place in two steps:

(a) neutralization of the particle's negative charge by the positively charged hydroxide.

(b) formation of flocs by bridging between the

particles as a result of the polymer chain adsorption. Flocculant characteristics such as adsorption ability, chain length, molecular weight, and electrostatic charge affect bridging and adsorptive capabilities. Media surface characteristics, pH, and water temperature are also factors which influence attachment.

Adin and Rebhin (1977) have concluded that if alum is used as the only pretreatment chemical in high flow rate filters, the floc formed was relatively ineffective in resisting shear forces so that the likelihood of the run terminating due to turbidity breakthrough was greater than due to the headloss buildup. Therefore, they recommended the supplementary use of a polyelectrolyte coagulant aid to strengthen the filter floc.

Interstitial straining is not actually a transport mechanism but a physical factor that relates to the entrapment of particles at the junction of media grains and at small pore openings. This removal mechanism is a function of the particle size/grain size ratio which according to Herzig et al. (1970) has to be at least 0.05 in a clean bed. For example, a minimum particle size of 10 microns can be effectively removed with a media bed of 0.2mm sized particles or smaller.

In deep granular beds, removal usually results from some combination of these mechanisms. For instance, surface cake-straining and removal by double-layer adsorption may occur simultaneously.

Mintz believed that the mechanism of removal is that of

continuous attachment and detachment with the rate of attachment being greater than detachment until there is no improvement in filter effluent quality. Accumulating filtrate is then held in equilibrium against the hydraulic shearing forces which want to tear and wash the solids deeper into the bed and finally through the filter (Ives,1965).

The hydraulic shear forces through a partially spent filter increase as the interstitial spaces are filled. These spaces become less effective in retaining solids and the burden of removal passes to the deeper and cleaner filter media (Ives,1961). Turbidity breakthrough occurs when the bed depth is exhausted. Shock loading or a rapid change in flow rate must be avoided since this usually generates inertial stresses that could drastically alter the filter equlibrium and induce premature turbidity breakthrough (Cleasby,1963).

Initial degradation of effluent quality during filtration is a short term effect in which a poor quality effluent is produced just after backwashing. Amirtharajah and Wetstein (1980) concluded that initial effluent quality (measured in terms of suspended solids) from a filter used over several runs can be characterized by:

(a) A lag period of low turbidity which corresponds to the volume of clean backwash water in the media.

(b) A dual peak period of high turbidity. The major source of suspended solids responsible for this turbidity breakthrough comes from a combination of the backwash water solids and the material released during interparticle

collisions of the media just after the backwashing control valve was closed.

(c) A relatively long period of turbidity decline which may be attributed to an intermixing of backwash water and fresh influent within the media bed.

2.3 REVIEW OF GIARDIA RELATED RESEARCH

2.3.1 Investigations into Cyst Removal During Filtration

Until recently, cyst removal in water filtration had focused on the problem of providing a potable water free of Entamoeba histolytica. Following an amoebic dysentry outbreak which occurred in Chicago in 1933, water filtration experiments were carried out at an experimental filtration plant belonging to the Chicago Department of Public Works. Two phases are described by Baylis (1936). In the second phase, tests with 0.9mm effective size rapid sand filter media showed a 99.99% removal of the spike dosed E. hystolytica cysts when the hydraulic loading rate was 4.8 m/hr. During World War II the U.S. Army and the U.S Public Health Service conducted a filter research program on E. histolytica cysts using flow rates between 15 and 23 m/hr and showed that with poor or non-existent coagulation a maximum of 88% cyst removal could be observed and that with proper coagulation up to 99.86% of the cysts could be removed (War Dept. Report #834 , from Logsdon, 1981). Since Giardia lamblia cysts are similar in size and shape to E. histolytica this research suggested that effective removal of Giardia cysts by filtration could be accomplished under the same conditions. However the cyst recovery techniques used in both of these experiments required the centrifugation of large amounts of water thus exposing the cysts to physical damage. Damaged cysts are difficult to positively identify with a microscope and if missed would result in overestimating the

actual removal rates.

Logsdon et al. (1981) conducted a rapid sand filter study using spiked Giardia muris cysts which they reasoned were a good surrogate for Giardia lamblia cysts. They used a dual media rapid sand filter that consisted of 460 mm of 1.27mm effective size anthracite over 150 mm of 0.36mm effective size sand with a hydraulic loading rate of 10.0 m/hr. Logsdon et al. (1981) determined that once filter ripening had occurred, low alum coagulant doses produced widely fluctuating filter efficiencies that ranged from 59% to 94% cyst removal while still meeting the 1.0 NTU maximum turbidity limit. By increasing the alum dose and adding polymers to achieve an effluent turbidity of 0.30 NTU, cyst removals of up to 99.9% were observed. After centrifugation, cysts were recovered on a polycarbonate membrane filter paper and identified on the basis of morphology using a hemocytometer. They concluded that once optimum coagulant dosing had been achieved, changes in the operation of the filter had a pronounced deleterious effect on the ability of the filter to remove cysts. A minimum turbidity of less than 0.30 NTU was required to achieve consistently effective cyst removal. Higher influent cyst concentrations resulted in higher removal percentages even though effluent turbidity remained the same. They reasoned that since their minimum detection limit was always greater than zero, the effect of a few cysts passing at a lower influent concentration was more significant than a few passing at higher spiked doses.

Logsdon et al. (1981) reported that a change in

filtered water turbidity from as low as 0.05 NTU to 0.10 NTU yielded a sharp increase in the passage of cysts. An increase turbidity during the filter ripening stage at the beginning of a filter run was also associated with an increase in the passage of cysts. Overall, they concluded that a granular media filter in a well operated water treatment plant should be greater than 99% effective in the removal of Giardia lamblia cysts.

DeWalle et al. (1984) conducted a study to evaluate the removal of Giardia lamblia cysts and cyst-sized particles in a pilot plant employing coagulation, sedimentation, and dual media filtration. The filters were made up of 508 mm of 0.92 effective size anthracite and 254 mm of 0.40 effective size sand. Cyst recovery techniques included filtration and centrifugation, followed by microscopic examination. Recovery efficiencies ranged from 72% to 85%. This study noted that greater than 99.9% removal of spiked cysts could be achieved under optimum treatment conditions. When only alum coagulant was used and the pH of the water was greater than 7.0 they noted that the performance of the filter was drastically reduced. They recommended that the minimum alum dose be not less than 10 mg/L and that the hydraulic loading on the filter could range from 4.8 to 9.8 m/hr. Outside these ranges, effluent turbidity and the passage of cyst-sized particles increased rapidly. Also, abrupt changes in plant operating conditions sharply decreased filter performance. When no coagulant was used during filtration, inconsistent and low removal efficiencies of Giardia cysts resulted. In

one run, only 48% of the dosed cysts and 47% of the turbidity was removed. In another run they found that producing a low turbidity effluent using alum or a polymeric flocculant aid was difficult when the water temperature was 3.0o C.

Hendricks et al. (1984) also researched the effectiveness of Giardia lamblia cyst removal in a pilot plant having coagulation, sedimentation, and filtration units. They simultaneously monitored coliform, total bacteria and particle removal in order to determine if there was a correlation between these and turbidity removal. The dual media filter bed consisted of 454 mm. of anthracite with an effective size of 0.90mm. and 762 mm. of sand with an effective size of 0.45mm. The filter loading rate ranged between 4.94 m/hr to 12.72 m/hr. Their results indicate that without coagulant, cyst removals were between 75% to 92%. With alum doses greater than 9.0 mg/L , more than 99% of the spiked cysts could be removed. In contrast to the DeWalle study, they were able to achieve greater than 99% removal at a raw water temperature of 3^{o} C. Finally, they concluded that greater than 90% removal in each of the other surrogate parameters that were monitored resulted in greater than 99% removal of the cysts.

CHAPTER 3. EXPERIMENTAL PROCEDURES

3.1 CYST MODELLING

In choosing a surrogate for Giardia lamblia cysts, physical as well as electrical parameters were considered. Ultimately, polystyrene divinyl benzene (DVB) latex spheres (supplied by Duke Scientific, Palo Alto, California) were selected because they were similar to the cysts in both size and shape and were easily enumerated under ultraviolet light using an epi-fluorescent microscope. Table 4 summarizes the similarities between the spheres and Giardia cysts.

Measurements of electrophoretic mobilities or zeta potentials of the latex spheres with respect to pH were conducted with a Zeta-Meter (Zeta-Meter Inc., New York) which had a plexiglass Riddick Type II electrophoresis cell with a 4.4 mm diameter tube and a cell constant of 65. The cell was equipped with a molybdenum anode and a platinum-iridium cathode which were spaced 100 mm apart. A 500 mL volume of river water spiked with latex spheres was used as the stock solution for the tests. The addition of HCl and NaOH provided pH control. Although there was considerable variation from pH 3.0 to pH 10.0, the zeta potentials of the spheres were always greater than -16 millivolts. By comparison, DeWalle et al. (1984) report Giardia lamblia zeta potentials from -28 millivolts to -36 millivolts within the pH range 7 to 11. A summary of the zeta potential data appears in Appendix III.

Table 4 Comparison of Giardia lamblia Cysts With Polystyrene DVB Latex Spheres

Characteristic	*Giardia lamblia* Cysts	Poly Styrene DVB Latex Spheres
Size	9µ-2Øµ x 5µ-15µ	6µ - 14µ[1]
Density	approx. 1.ØØ+	1.Ø5
Shape	ovoid	spherical
Surface	smooth	smooth
Cell Wall	flexible	rigid
Zeta Potential	-26mv @ pH 5.5[1]	see section 3.1

[1] See Appendix III for detailed size distribution.
[2] Dewalle et al., 1984.

3.2 SPHERE RECOVERY TECHNIQUE

Volumetric samples were taken from the bench scale plant at the raw water, post clarifier and post filter locations. Sample size was dependent on the number of spheres expected to escape treatment. Since it was difficult to count and size any more than 50 spheres from any one sample, a rough preliminary estimate of removal efficiency was made and the sample volumes were adjusted accordingly.

Using a Millipore 25 mm. glass micro analysis frit-support filter (Millipore Inc., Bedford, Mass.) aliquots of sample were filtered across a 5µm pore size, 25mm diameter polycarbonate membrane filter paper (Nucleopore Ltd. Pleasanton, California). A constant vacuum pressure of 137.9 kPa was applied in order to draw the sample water through the filter paper (Plate 1). Concentrated hydrochloric acid was added to the flask to reduce the pH to below 2.0 and dissolve any suspended lime floc. Thus, premature clogging of the membrane was avoided. Since the spheres were non-deformable and had a minimum size of 6 microns, 100% recovery was expected. In order to verify this, the filtrate from random pilot plant samples was retained and using the same procedure as above, was refiltered. No latex spheres were detected in the filtrate of any of the ten samples that were examined.

The step-by-step technique is as follows:

(a) The filter membrane was placed with tweezers onto the fritted glass pedestal of the suction funnel. The graduated cylinder top was then attached and clamped down taking care not to ripple the surface of the membrane.

(b) Acidified sample from the volumetric flask was slowly poured into the funnel and filtered at a suction pressure of 137.9 kPa.

(c) The sample flask was rinsed three times with 10 mL to 50 mL of distilled water. The rinse water was collected and filtered.

(d) The inside wall of the filter funnel was rinsed with distilled water to ensure that all the spheres had been washed onto the membrane.

(e) The funnel top was unclamped and the wet filter membrane was carefully removed with tweezers.

(f) The membrane was then stored in a dust-free box until all of the samples had been collected and were ready for counting.

(g) The funnel was rinsed with distilled water and using tweezers a fresh filter membrane was placed on the pedestal.

(h) This procedure was repeated for each new sample.

Plate 1. Sphere Recovery Technique

3.3 SPHERE ENUMERATION

A Zeiss Model #872-E (Zeiss Ltd., West Germany) epi-fluorescent microscope was used for enumeration. When the latex spheres were exposed to ultraviolet light at a wavelength of 490 nm they fluoresced in a characteristic manner that made them distinguisable from the background. In the early stages of the study, some particles were seen to so closely resembled the latex spheres that it was possible to erroneously include them into the total count. In order to gauge this effect, non-spiked samples of raw water were collected prior to each run and scanned for particles that might possibly be mistaken for spheres. Once a raw water background was established, percentage reductions due to water treatment were assumed to be the same as that which was observed for the latex spheres. It was then possible to calculate the theoretical background count for each of the downstream locations and this value was subtracted from the actual number counted. As more experience was gained with the technique, less background was observed. In all of the runs however, the background accounted for a very small percentage of the total number of spheres seen. Results of the sphere counts on a sample-by-sample basis appear Appendix I.

The step-by-step microscopy procedure is as follows:

(a) A drop of distilled water was added to a clean straight slide.

(b) The filter membrane was removed from the dust-free box and placed on the drop of water. The filter membrane flattened and adhered to the surface of the glass.

(c) The slide containing the sample was placed on the stage of the microscope and the power was switched on.

(d) Using the 400 x objective the whole filter membrane was systematically scanned (either horizontally or vertically) .

(e) Using the hair-line grid, each sphere was identified with respect to size.

(f) The filter paper was kept wet by application of drops of water as this created a darker background from which spheres could be more easily spotted.

(g) This procedure was repeated for each sample taken.

The criteria used for identification of latex spheres included :

: size (6μ to 14μ)

: shape (spherical)

: characteristic fluorescence (semi-transparant whitish-green with some variance in intensity)

: characteristic refractive pattern when the sphere is subjected to a horizontal light source in the visible spectrum

Plates 2, 3 and 4 show positive identifications of typical latex spheres at a magnification of 400x. The

Plate 2. Latex Sphere Identification at 400x
(with horizontal incandesent light source)

Plate 3. Latex Sphere Identification at 400x
(with 490 nm ultraviolet light source)

Plate 4. Latex Sphere Identification at 400x
(with horizontal incandescent and UV light sources)

Plate 5. Background Particle at 400x
(with horizontal incandescent and UV light sources)

background matrix is generated by the 5mm pore holes of the filter membrane. Plate 5 shows a particle that is not a latex sphere and although similar in size and shape, was rejected because of its colour (yellow) and its very bright intensity.

3.4 PARTICLE SIZE DISTRIBUTION

Particle-size distribution analyses were performed on the same samples that were scrutinized for latex spheres. An electronic particle counter, Coulter Counter Model TA II (Hialeah, Florida) with a 280 μm aperture tube was used and this corresponded to a 5.6 μm to 112 μm theoretical particle measuring range. Isotron II was used as the electrolyte and the standard calibration and operation procedures as outlined in the manual were followed.

Neis et al. (1976) and Treweek and Morgan (1977) recommended using the largest sized aperture that would accomodate the desired size range because this would reduce the problem of shear effects on the aggregates as they passed through the aperture. Beard and Tanaka (1977) demonstrated that it was possible to store samples for up to 24 hours at 4^{o} C. without significant particle redistribution. All the samples in this study were stored at 5^{o} C. and analyzed within 5 hours after the end of each run.

3.5 LABORATORY SCALE WATER TREATMENT PLANT

The laboratory-scale pilot water treatment plant was designed and constructed by the author. The design philosophy was to build a bench scale water treatment plant that could simulate typical water treatment practice in Alberta. An effort was made to model the operation of the plant after the full-scale E. L. Smith water treatment plant example. However exact duplication was not entirely practical. Table 5 provides a comparison of the general characteristics the two.

Table 5
General Comparison of the E. L. Smith Water Treatment Plant With the Laboratory Scale Plant

Characteristic	Laboratory Scale Pilot Plant	E. L. Smith Plant
Raw Water Source	North Saskatchewan River	
Water Temp.	2°C. - 3°C.	
Coagulation and Softening	Alum and lime are added together upstream of the rapid mixer.	
Flocculator	Square tank with paddle stirrer. Detention time = 25 minutes	Upflow reactivator with recycling. Detention time 3-4 hrs. Tube settlers in clarifier.
Clarifier	Two rectangular cross-flow tanks in series. Detention time = 2-2.5 hrs.	
Recarbonation	Carbon Dioxide Gas	
Filtration	Dual media declining flow Hydraulic loading rate 136 L/min.m^2	
Backwashing	Air scour prior to high rate Backwashing at 733.1 L/min.m^2	

Raw water was obtained from the North Saskatchewan River and transferred to 220 litre barrels that were stored inside a walk-in refrigerator. All of the tanks in the plant were constructed of poly-ethylene and encased in pipe fitter's sheet insulation for temperature control. Foam insulated Tygon lines were used for the piping. The single stream operated at a flow rate of approx. 1.00 litre/min. which was sufficient to yield a filter loading rate of 137.8 $L/min.m^2$. The apparatus was mounted on scaffolding that measured 2.5m x 1.2m x 3.7m. (Plate 6). A schematic of the design can be found in Figure 7. Step-by-step operation of the plant is described in Appendix II. The physical dimensions and design factors for the individual units are given below.

3.5.1 Cooling Tank and Refrigeration Unit

A 100 litre insulated drum with a copper radiator coil functioned as the cooling reservoir (Plate 7). A Koolmaster Model 100 refrigeration unit pre-cooled the raw sample water to between 30C. to 40C. prior to each run. Detention time in the tank was 60 minutes. Recycled raw water from the upper reservoir coupled with inlet turbulence ensured continious mixing.

3.5.2 Upper Reservoir

Raw water from the cooling tank was pumped to the upper reservoir by means of a Little Giant, Model PPS-1 centrifugal pump (Little Giant Ltd., Oklahoma City, Okla.). A continious overflow was maintained. The constant hydraulic

Plate 6. Laboratory Scale Water Treatment Plant

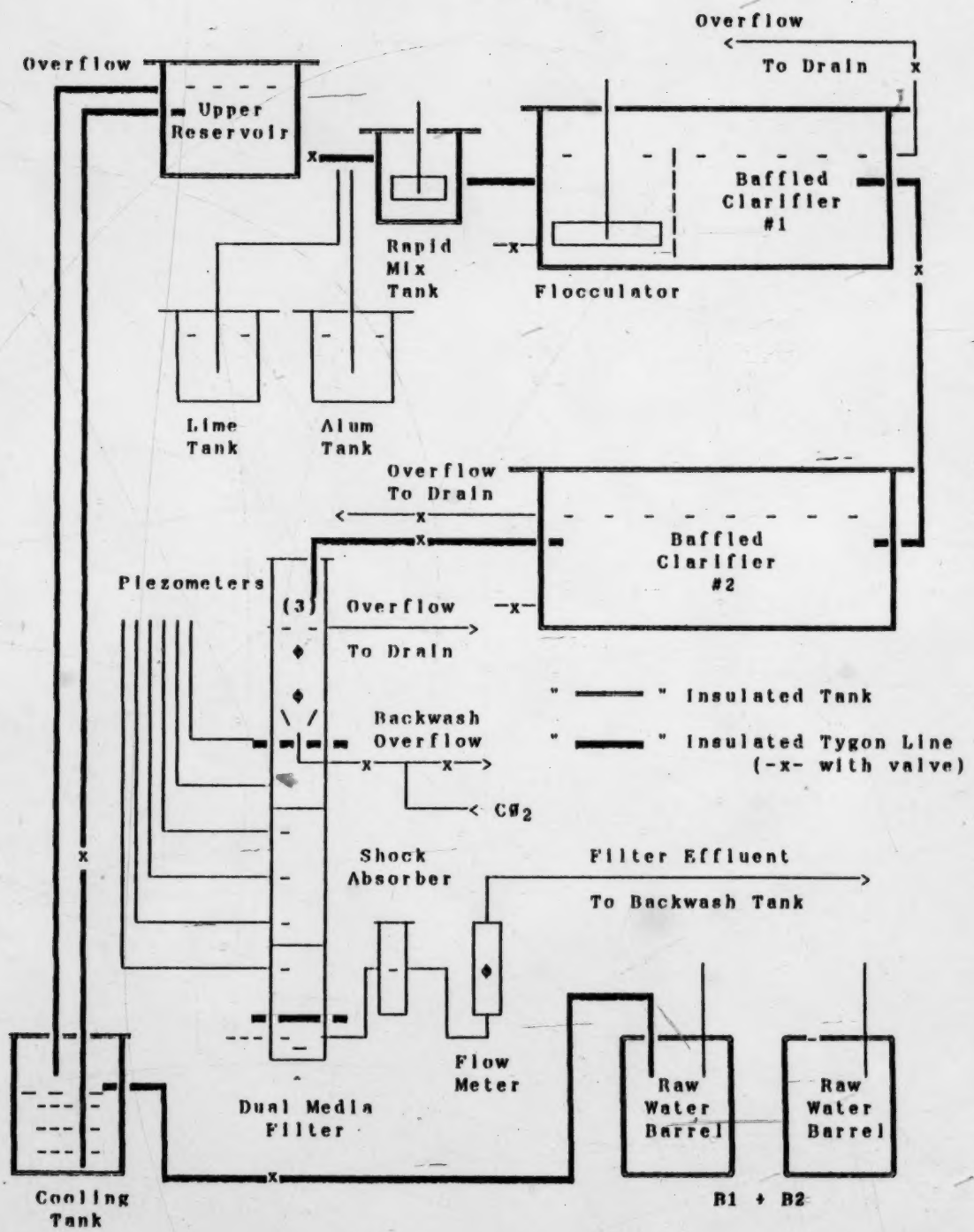


Figure 7. Schematic of the Bench Scale Water Treatment Plant

head in the reservoir provided relatively stable flow (± 5%) to the downstream units. Discharge out of the reservoir was regulated by a metering valve located on the outlet line at the base of the tank.

3.5.3 Alum and Lime Chemical Feed System

Diluted alum and lime were added prior to rapid mixing and were stored in 20 litre polyethelyne tanks. Masterflex peristaltic pumps (Cole Parmer Ltd., Chicago. Ill.) with 0 to 100 rpm variable speed drives were used to feed the chemicals into the raw water stream (Plate 8). Chemical feed rates were monitored with Gilmont Size No. 3 variable area flowmeters (Cole Parmer Ltd., Chicago, Ill.). Flow adjustments were based on the experimental dosing rate required.

3.5.4 Rapid Mixer

The dimensions of the rapid mixing tank were 150mm x 100mm x 100mm. At a flow rate of approx. 1.0 L/min the average theoretical detention time was 1.5 minutes. A variable speed drive connected to a rectangular impeller blade yielded velocity gradients ranging from 0 sec^{-1} to 600 sec^{-1}.

3.5.5 Flocculator

Slow mixing was accomplished in a plexi-glass tank that was built into the first clarifier. Measured from the height of the overflow weir, the dimensions were 300mm x 300mm x

Plate 7. Cooling Tank

Plate 8. Rapid Mixer and Chemical Injection Points

300mm and the theoretical detention time was 27 minutes. A variable speed drive and a rectangular bladed paddle provided a velocity gradient which ranged from 0 to 150 sec^{-1}.

3.5.6 Clarifiers

The two polyethylene clarifiers 600mm x 300mm x 450mm were used in series. At the 1.0 L/min design flow rate the theoretical detention time was 55 minutes in the first and 80 minutes in the second with a surface loading rate was 7800 $L/min.m^{-2}$. A inlet chamber along with an around-the-end baffling system was employed in order to minimize the dead spaces and maximize clarifier efficiency. Plate 9 shows the construction of both the clarifiers and the flocculator. A dye test using methylene blue as the indicator was performed in order to visually detect any tank short circuiting. None was observed.

3.5.7 Filter Column

A 95 mm I.D. plexiglass column housed a dual media filter bed which consisted of 400 mm of 1.1 mm effective size anthracite (uniformity coefficient = 1.2) over 300 mm of 0.38 effective size sand (uniformity coefficient = 1.3). The media was supplied by the City of Edmonton and is the same as that which was in use at the E.L. Smith and Rossdale Water Treatment Plants. Influent and effluent filter turbitities were monitored at timed intervals during each run with a Hach (Hach Ltd, Ames, Iowa) Model 2100A turbidimeter. Following a design recommended by Gould

Plate 9. Clarifiers and Flocculator

(1979) and Cleasby (1963) a shock absorber was installed on the filter effluent line in between the column and the filter flow control valve. This dampened the inertial forces felt by the media when flow was restarted after backwashing. Plate 10 provides a close up view of the filter column, the media, and the piping. Although for this experiment a declining flow rate pattern was used, with a few minor adjustments it would be possible to change to a constant rate regime. A funnel-shaped hopper acted as an overflow weir in the collection of backwash water.

3.5.8 Recarbonation

For pH readjustment, carbon dioxide was bubbled through the backwash water funnel during filter runs (Plate 11). The upper 300mm of the column functioned as a recarbonation chamber with a detention time of approx. 2 seconds. The additional turbulence generated by the bubbling did not disturb the filter bed.

3.5.9 Finished water

A portion of the filtered water was collected in a 100 litre insulated holding tank and was saved for backwashing purposes.

3.6 EXPERIMENTAL DESIGN

Jar tests were performed on raw river water in order to optimize the rapid mix and flocculator paddle speeds. A scale-up factor of 1.0 was used. The rapid mixer and the

Plate 10. Dual Media Filter Column

Plate 11. Recarbonation Chamber

flocculator drives were set at 100 rpm and 45 rpm respectively, and remained unchanged for the course of the experimentation.

3.6.1 Run Schedule

Since only 5000 litres of a consistent batch of raw water was available, the study was limited to 11 runs. Runs #1, #2, and #3 were spent shaking down the system. Runs #4, #5, and #6 were designed to determine the reproducability of the results while using intermediate chemical dosages. In Runs #7 and #8 the effect of varying the alum dose with respect to a high concentration of lime was examined. With Runs #9 and #10 the effect of varying the alum dose in the absence of lime was investigated. In Run #11 no coagulant was used.

All samples for sphere counts and particle-size analysis were taken after the filter turbidities had stabilized (approx. 60 min. from start-up) and the average run length was 4 to 5 hours.

3.6.2 Chemicals

For coagulation, aluminum sulphate as $(Al_2(SO_4)_3.14H_2O$ was used.

For hardness reduction, calcium hydroxide as $Ca(OH)_2$ was used.

4. RESULTS AND ANALYSIS

4.1 INTRODUCTION

As a surrogate for Giardia lamblia the latex spheres performed well. It may be argued that because the zeta potentials of the spheres were less negative (i.e. closer to zero) than those reported for the live cysts, the spheres did not act as an adequate model during water treatment. However, for the anticipated mechanism of removal in the clarifier, the effect of a smaller electric charge was not important. In the coagulation step for instance, the pH for all of the runs was higher than the alum isoelectric point of 6.1. Thus, the aluminum hydroxyl species that were present were mostly negatively charged (i.e. $Al(OH)_4^-$). The predominant mechanism of removal in the clarifier was enmeshment in a sweep floc and destabilization of a negatively charged sphere due to charge neutralization could not occur to any great extent because the concentration of positively charged aluminum species was far too low. Therefore for these runs, electric charge was not as significant as particle size. In the filter, the transport mechanisms of both Giardia and the latex spheres were similar because this is a size related phenomenon. The spheres had a smaller electro-negative charge and consequently smaller "double layer" repulsive forces had to be overcome in order to attach to the negatively charged media. The results from these runs therefore showed higher sphere removal efficiencies in the filter than what might be expected with

live cysts. Although the spheres did not exactly model the behaviour of live cysts, they did yield results that provided some information as to what might be considered an upper limit on cyst removal efficiencies in the filter. In the case of straining it has been speculated that the cyst's ability to deform its cell wall (de Walle et al., 1982) can aid it in slipping through the filter bed. By comparison, the rigid latex spheres in retaining their shape would have more potential for interception and capture by the media and again yield higher removal efficiencies.

The vacuum filtration and epi-fluorescent microscopy procedures that were developed had the potential for 100% recovery. Other experimenters have found that in the concentration of Giardia cysts by centrifugation, a number of the cysts are ruptured or destroyed and are not counted. Nevertheless, by repeating the procedure a number of times a statistical data base could be developed from which a recovery rate may be calculated. Clarifier and filter performance was then measured assuming a percentage loss associated with each sample collected. The problem with this method is that by observing zero cysts in the filter effluent 100% removal efficiency is not guaranteed since there is always a question of the fate of the cysts which have disappeared.

Recent advances have pushed the recovery rate to greater than 90% but some of the earlier work was based on very low recoveries (i.e. 68%). Because the spheres are rigid they are not damaged by the vacuum filtration technique and are

not likely to be squeezed and lost into the pore holes of the filter membrane. Thus, the recovery rate is a function of the technician's ability to recognize the spheres on the filter paper. Enumeration using epi-fluorescent microscopy required a great deal of time when the whole area of the filter was scanned. However, the spheres were found to be very distinct from the background. Some problems were encountered when the sample volume was too large or the sample was too dirty. The detritus found in the water could cover the spheres and mask their natural reflective capabilities, thus making them more difficult to see. This can be overcome by vacuum filtering a smaller sample volume. Alternatively, it is possible to substitute specially coated spheres which will fluoresce much more intensely under ultraviolet light. Enumeration of the spheres would be faster because a lower power of magnification could be used and positive identification of the spheres would become easier.

Raw North Saskatchewan River water was used in order to more closely simulate the low turbidity, cold, and low suspended solids raw water conditions that are typically encountered at the City of Edmonton water treatment plants in the winter. Consequently, the availability of refrigerated storage space imposed a limit on the amount of water that could be stored and the number of runs that could be performed on a consistent batch of water. In all, there was enough raw water for eleven trials. Runs #1 to #3 were used in order to shake down the operation of the pilot plant and no latex sphere dosing was performed.

Table 6 summarizes the operating conditions of each run as well as the effluent turbidities and pH at each sampling point after the filter had stabilized. Filter run lengths were typically 3.0 to 4.0 hours.

The raw data relating to the individual latex sphere counts can be found in Appendix I.

4.2 LATEX SPHERE REMOVALS

Analysis of variance comparisons (ANOVA) were made in order to determine if there were similarities in the mean percentage of latex sphere removals between selected runs. Because the number of runs was limited, only the effects of making gross changes in chemical dosing rates was examined

Run #4 and Run #5 (similar alum and lime dosages) were statistically compared in order to determine if latex sphere removal rates could be duplicated when the operating conditions remained unchanged. Run #6 was not included in this analysis because an equipment failure during the run significantly changed the clarifier and filter flow rates.

A two-way ANOVA was used to compare Runs #7 and Run #8 with Runs #9 and Run #10 in order to determine whether or not the difference in percentage removals of latex spheres observed in the clarifier and in the filter were significant and if there were any interactive effects between the alum and lime.

An F test was performed on the data at a level of significance of 5% ($a=0.05$).

The percentage removals for each run are given in

Table 6
Summary of Run Operating Conditions

Run	Alum	Lime	Run	pH		Turb. (NTU)	
#	(mg/L)	(mg/L)	(hrs)	3[1]	4[2]	3[1]	4[2]
ELS	15.Ø	48.Ø	n.a.	8.9	8.4	1.1	Ø.24
4	14.9	88.Ø	4.Ø	9.4	8.3	3.6	Ø.25
5	15.6	87.5	3.5	9.3	8.2	4.Ø	Ø.3Ø
6	15.6	87.5	run interrupted - power failure				
7	46.5	2Ø4.8	3.5	1Ø.4	8.2	2.8	Ø.13
8	5.1	2Ø3.3	3.Ø	1Ø.5	8.4	2.5	Ø.13
9[3]	5.Ø	Ø.Ø	3.Ø	7.8	7.7	2.2	Ø.22
1Ø[3]	46.5	Ø.Ø	3.Ø	7.3	7.3	1.1	Ø.22
11[3]	Ø.Ø	Ø.Ø	3.Ø	8.Ø	8.Ø	-	-

[1] Location #3 is at the pre-filter influent stage.
[2] Location #4 is at the post filter stage.
[3] Recarbonation for pH control was omitted.

Table 7
Data For Statistical Analysis of % of Latex Spheres Removed

Run	Clarifier			Filter			Overall		
#	Pre	Post	%	Pre	Post	%	Pre	Post	%
4	2500	124	94.05	132	45	65.91	2500	45	98.20
	2500	132	94.72	132	39	70.45	2500	39	98.44
	2500	136	94.56	132	**	**.**			
Avg.	2500	132	94.77	132	42	68.18	2500	42	98.32
5	2700	120	95.56	116	34	70.69	2700	34	98.79
	2700	120	95.56	116	31	73.28	2700	31	98.85
	2700	108	96.00	116	34	70.69	2700	34	98.74
	—			116	30	74.14	2700	30	98.89
				116	22	81.03	2700	22	99.19
				116	27	76.72	2700	27	99.00
				116	22	81.03	2700	22	99.19
Avg.	2700	116	95.69	116	29	75.34	2700	29	98.94
6	1700	104	93.88	108	12	88.89	1700	12	99.29
	1700	108	93.65	108	6	94.44	1700	6	99.65
				108	8	92.59	1700	8	99.53
				108	12	88.89	1700	12	99.29
				108	6	94.44	1700	6	99.65
				108	10	90.74	1700	10	99.41
				108	12	88.89	1700	12	99.29
				108	12	88.89	1700	12	99.29
				108	11	89.81	1700	11	99.42
Avg.	1700	106	93.76	108	10	90.84	1700	10	99.41
7	4700	124	97.36	128	16	87.50	4700	16	99.66
	4700	132	97.19	128	16	87.50	4700	16	99.66
	4700	132	97.19	128	12	90.63	4700	12	99.74
	4700	128	97.28	128	12	90.63	4700	12	99.74
				128	10	92.19	4700	10	99.79
				128	10	92.19	4700	10	99.79
				128	12	90.63	4700	12	99.74
Avg.	4700	128	97.26	128	12	90.18	4700	12	99.73
8	5800	196	96.62	198	8	95.96	5800	8	99.86
	5800	196	96.62	198	10	94.95	5800	10	99.83
	5800	204	96.48	198	8	95.96	5800	8	99.86
	5800	194	96.66	198	8	95.96	5800	8	99.86
				198	8	95.96	5800	8	99.86
				198	10	94.95	5800	10	99.83
Avg.	5800	198	96.59	198	9	95.62	5800	9	99.85

Table 7 (cont.)
Data For Statistical Analysis of % of Latex Spheres Removed

Run	Clarifier			Filter			Overall		
#	Pre	Post	%	Pre	Post	%	Pre	Post	%
10	6000	760	87.33	740	60	91.89	6000	60	99.00
	6000	736	87.33	740	54	92.70	6000	54	99.10
	6000	756	87.40	740	59	92.03	6000	59	99.02
	6000	780	87.00	740	61	91.76	6000	61	98.98
	6000	730	87.83						
	6000	650	89.17						
Avg	6000	740	87.74	740	58	92.09	6000	58	99.03
9	9600	910	90.52	1140	26	97.72	9600	26	99.73
	9600	1040	89.17	1140	28	97.54	9600	28	99.71
	9600	950	90.10	1140	28	97.54	9600	28	99.71
	9600	1276	86.71	1140	22	98.07	9600	22	99.77
	9600	1364	85.79	1140	26	97.72	9600	26	99.73
	9600	1304	86.42	1140	26	97.72	9600	26	99.73
					22	98.07	9600	22	99.77
					24	97.89	9600	24	99.75
Avg.	9600	1140	88.12	1140	25	97.97	9600	25	99.74
11	5000	1360	72.80	1360	124	90.88	5000	124	97.52
	5000	1320	73.60	1360	116	91.47	5000	116	97.68
	5000	1240	75.20	1360	112	91.76	5000	112	97.76
	5000	1440	71.20	1360	112	91.76	5000	112	97.76
				1360	96	92.94	5000	96	98.08
				1360	96	92.94	5000	96	98.08
				1360	108	92.06	5000	108	97.84
				1360	102	92.50	5000	102	97.96
				1360	103	92.43	5000	103	97.94
				1360	97	92.87	5000	97	98.06
Avg.	5000	1360	73.20	1360	107	92.16	5000	107	97.87

4.2.1 Analysis of Variance: Run #4 and Run #5

Post clarifier sphere counts:

(a) Null hypothesis H_o: $U_1 = U_2$

(b) Computation:

ANOVA

	S. S.	df	M. S.	F
Treatments	1.30	1	1.30	20.68
Errors	0.25	4	1.06	
Totals	1.55	5		

(c) Since $F_{1,4,}$ (a=0.05) = 7.71 is less than 20.68 reject the null hypothesis.

$F_{1,4,}$ (a=0.01) = 21.21 is greater than 20.68 therefore accept the null hypothesis.

(d) Conclusion: The total % of latex sphere removal in the clarifier between Run #4 and Run #5 is not the same at the 5% level of significance.

: The total % of latex sphere removal in the clarifier between Run #4 and Run #5 is the same at the 1% level of significance.

Post filter sphere counts:

(a) Null hypothesis H_o: $U_1 = U_2$

(b) Computation:

ANOVA

	S. S.	df	M. S.	F
Treatments	80.38	1	80.38	4.47
Errors	126.05	7	17.98	
Totals	206.27	8		

(c) Since $F_{1,7}$ (a=0.05) = 5.59 is greater than 4.47 accept the null hypothesis.

(d) Conclusion: The total % of latex sphere removal in the filter between Run #4 and Run #5 is the same at the 5% level of significance.

4.2.2 Two Way Analysis of Variance

Runs #7 and Run #8 vs Run #9 and Run #10

The relationship of the chemical doses used in runs are:

	Low Alum	High Alum
Low Lime	Run #10	Run #9
High Lime	Run #8	Run #7

Post clarifier sphere counts:

(a) Null hypotheses:

(i) Ho: U1 = U2

(ii) Ho: There is no significant interaction between the independent variables

(b) Computation:

ANOVA

	S. S.	df	M. S.	F
Lime	390.96	1	390.96	25.95
Alum	0.000	1	0.000	0.00
Interaction	1.456	1	1.456	0.96
Error	24.157	16	1.510	
Total	416.566	19		

(c) Since $F_{1,16}(a=0.05) = 4.49$ is less than 25.95 reject the null hypothesis for lime

Accept the null hypothesis for alum since 4.49 is greater than 0.00.

Accept the null hypothesis for the interaction since 4.49 is greater than 0.96.

(d) Conclusion: The effect of varying the lime dose on the removal of latex spheres in the clarifier is significant at the 5% level.

: The effect of varying the alum dose on the removal of latex spheres in the clarifier is not significant at the 5% level.

: There is no significant interaction

(within the limits of experimentation) between alum and lime dosages in the clarifier.

Post filter sphere counts:

(a) Null hypotheses:

(i) Ho: U1 = U2

(ii) Ho: There is no significant interaction between the independent variables

(b) Computations:

ANOVA

	S. S.	df	M. S.	F
Lime	63.675	1	63.675	52.98
Alum	220.326	1	220.326	181.31
Interaction	-38.351	1	-38.351	-29.41
Error	245.241	21	1.202	
Total	270.893	24		

(c) Since $F_{1,21}$ (a=0.05) = 4.32 and is less than 52.98, 183.31, and |-29.41| reject the null hypotheses.

(d) Conclusions: The effect of varying the alum and lime doses in the removal of latex spheres in the filter is significant at the 5% level.

: Filter performance is affected significantly due to some interaction between the alum and lime dosages.

4.2.3 ANOVA Summary

From Run #4 and Run #5 the removal of the spheres in the filter is the same in both runs at the 5% level of

significance and the removals in the clarifier are not significantly different at the 1% level.

The two-way ANOVA indicates that within the parameters of this experiment the effect of increasing the lime dose in the clarifier from 0 mg/L to approximately 200 mg/L is significant in the removal of latex spheres. An examination of the data shows that the addition of lime in Runs #7 and #8 produced a clarifier effluent that had a greater percentage of spheres removed than when lime was not added. By comparison, a change in alum dose from 5 to 45 mg/L did not significantly affect sphere removal in the clarifier. The ANOVA shows that the effect of the addition of lime was far more significant than that of alum in the removal of spheres. So powerful was the effect of the addition of lime that any effect produced by the change in alum dose was completely overshadowed. An interaction between the alum and lime effects could not be detected at the 5% level of significance.

Two-way ANOVA indicates that the effect of varying the lime dose from 0 to 200 mg/L was significant in the removal of latex spheres in the filter. Examination of the data shows that the best filter removals occurred when high alum and zero lime was used. Also, the effect of a change in alum dose was more significant in the filter than the effect produced by the addition of lime. There appeared to be significant negative interaction between alum and lime in the filter. The ANOVA suggests that within the parameters of this experiment that the presence of lime in the carryover from the clarifier

decreases the ability of the filter media to remove latex spheres. A change was made in pilot plant operation that is worthy of some consideration. Whenever lime was used, recarbonation was necessary in order to lower the pH to between 8.2 and 8.4. This procedure simulates full scale operation. When alum was used alone, pH adjustment by recarbonation was not required since the filter effluent pH ranged from between 7.3 to 7.7. If particle attachment to the filter media is pH dependent, then the best removals might be expected at the lower pH where a higher concentration of positively charged alum species may be found. The best removals were in fact observed in Run #10 in which the highest alum dose and zero lime was used resulting in the lowest pH. Better alum complex formation was expected at lower water pHs. The high pH experienced with the addition of lime might have hindered alum floc formation and therefore produced a predominantly non-gelateneous weak floc that would not be easily captured within the filter bed. However, additional work is needed in order to more clearly determine the relative effects of the addition of lime (and pH) with respect to particle attachment and filter performance. The results of this experimentation suggest that separation of the lime softening and alum coagulation would result in improved filter performance.

4.2.4. Sphere Size Distributions

As the spheres were enumerated they were categorized into size ranges. The raw sphere counts and size range

breakdowns are detailed in Appendix I. Figure 8 summarizes the clarifier effluent sphere size distribution results on a run-by-run results. Figure 9 summarizes the results from the filter. A series of ANOVAS were performed on the raw sphere counts of each run with the object of comparing the percent removals in the 6μm - 8μm range with the 12μm - 14μm range in order to determine if the differences that appear on the graph are in fact significant. A brief summary of the ANOVA results appear below in Tables 7 and 8. The means of the percentage removals in each of the size ranges were assumed to be equal if F was less than $F_{v1,v2}$ (a=0.05).

Although there were a few exceptions, in general the percentage removals of 6μm - 8μm spheres in the clarifier and the filter were significantly different than the removals of the 12μm - 14μm sized spheres. An examination of the data from the graphs show that the larger particles are more efficiently removed. If entrapment by a sweep floc is the primary mechanism of removal in the clarifier then a larger particle would have more opportunity to be captured. The ability of a filter media to more efficiently remove larger particles as opposed to smaller ones is to be expected. The data in Figure 9 also emphasizes that an increase in passage of Giardia cysts through a filter can be anticipated if the cyst are able to deform, since a reduction in the effective area perpendicular to the stream flow line is equivalent to the passage of smaller particles.

Figure 8 Clarifier Effluent Summary
% Latex Spheres Removed vs Particle Size

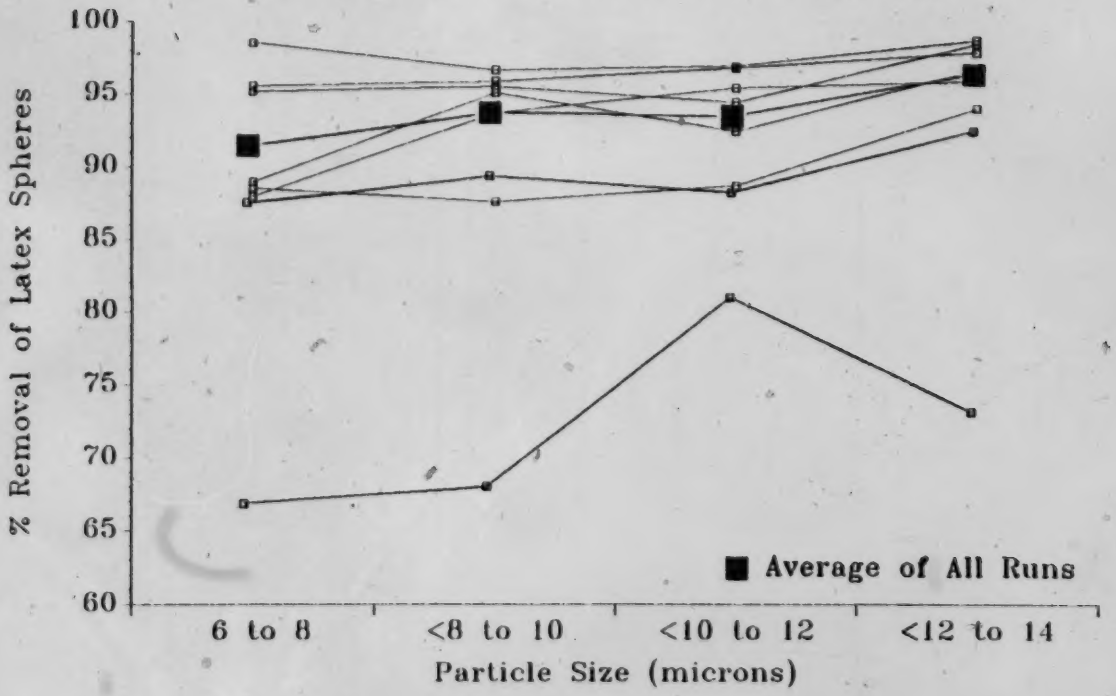
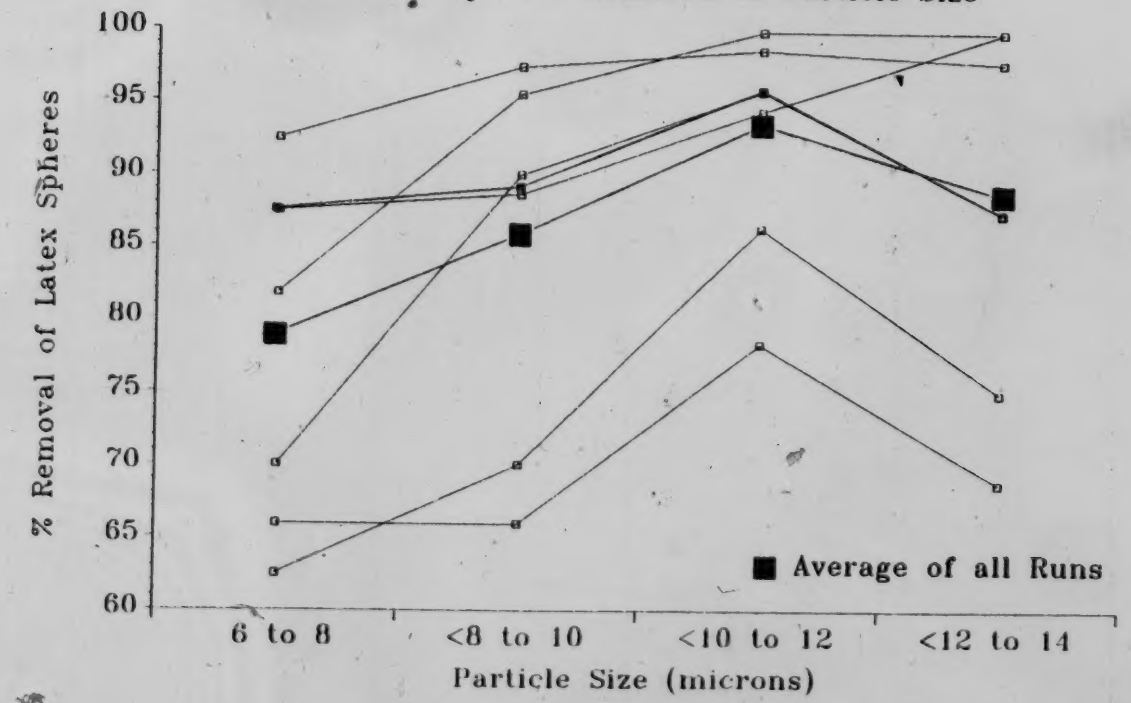


Figure 9 Filter Effluent Summary
% Latex Spheres Removed vs Particle Size



4.2.5 Particle-Size Distributions

The results of the Coulter Counter analyses are presented in Figure 10 to Figure 16. A channel vs particle-size chart can be found in Appendix III.

Figure 10 shows results for the Coulter Counter analysis of the E. L. Smith process stream samples taken concurrently with the collection of the raw river sample water. From raw water to filter effluent there appears to be a general reduction in particle count in all the size ranges after each stage of treatment.

The values obtained from the E. L. Smith post clarifier (i.e. pre-filter prior to recarbonation) and post filter stages were used for comparison in order to gauge pilot plant performance.

Figures 11 and 12 reflect the clarifier and filter performance of Runs #4 and #5 respectively. Removal of particles in the Giardia cyst size-range by the clarifier and filter of the lab-scale plant is not as efficient as that of the full-scale plant. A higher lime dosage was used and this produced additional lime carryover in the pilot plant clarifier effluent. Since the solids loading rate on the filter was higher than at E.L. Smith, the filter produced an effluent that also had a higher level of particles. A comparison of the pre and post filter turbidities confirms this result. Low floc resistance to the hydraulic shear forces within the filter bed could account for this behaviour.

Table 8

Summary of Sphere Size Distribution ANOVAS for the Clarifier

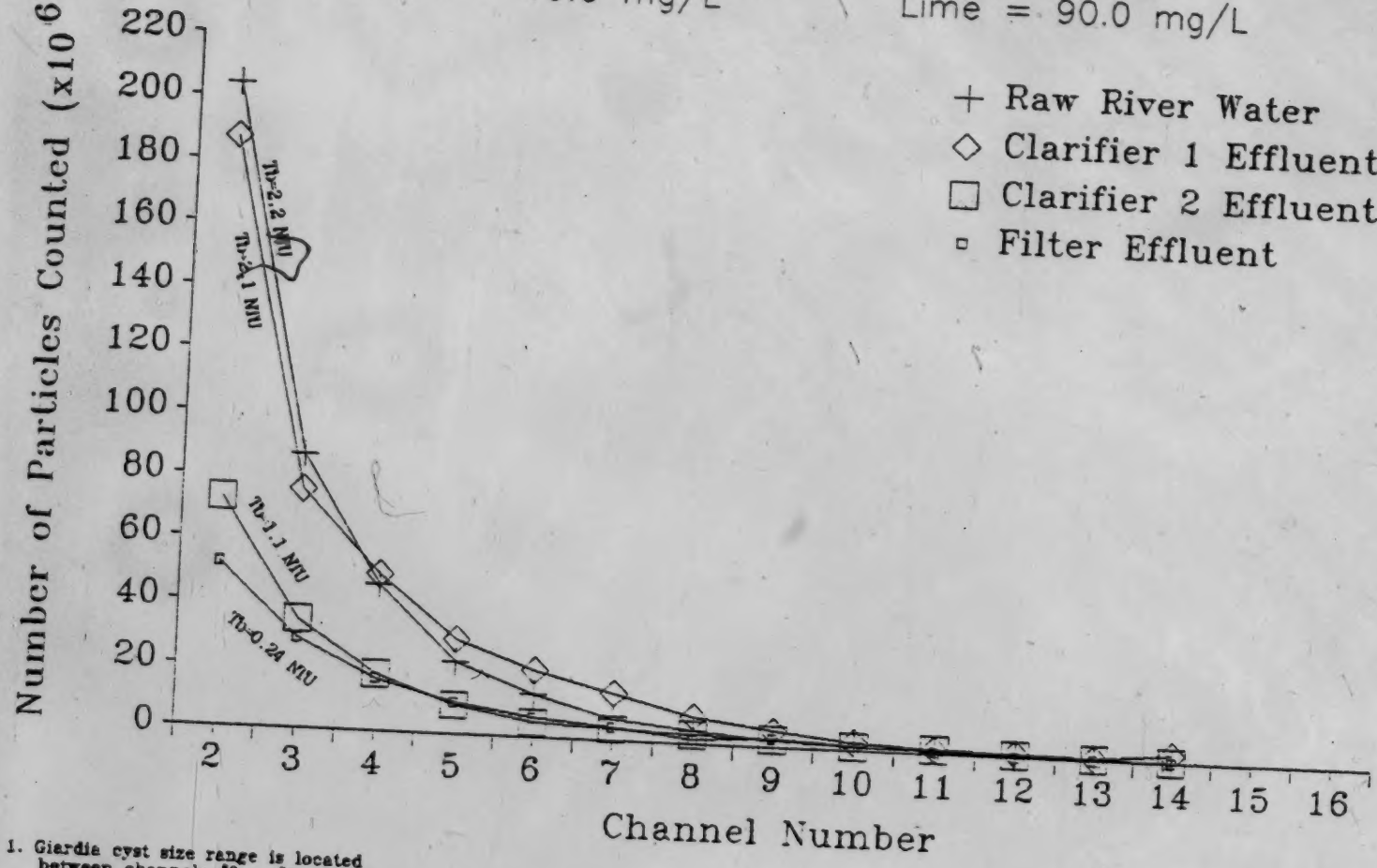
Run #	Degrees of freedom		F	$F_{v1, v2}$ (α=.05)
	Between means	Between counts		
4	1	4	66.67	7.71
5	1	14	3.45	4.60
7	1	6	9.00	5.99
8	1	6	19.49	5.99
9	1	10	31.89	4.96
10	1	10	3.88	4.96
11	1	7	0.15	5.59

Table 9

Summary of Sphere Size Distribution ANOVAS for the Filter

Run #	Degrees of freedom		F	$F_{v1, v2}$ (α=.05)
	Between means	Between counts		
4	1	3	1.56	10.1
5	1	13	20.57	4.67
7	1	15	11.29	4.54
8	1	10	40.29	4.96
9	1	11	31.89	4.84
10	1	11	3.88	4.84
11	1	18	4.50	4.41

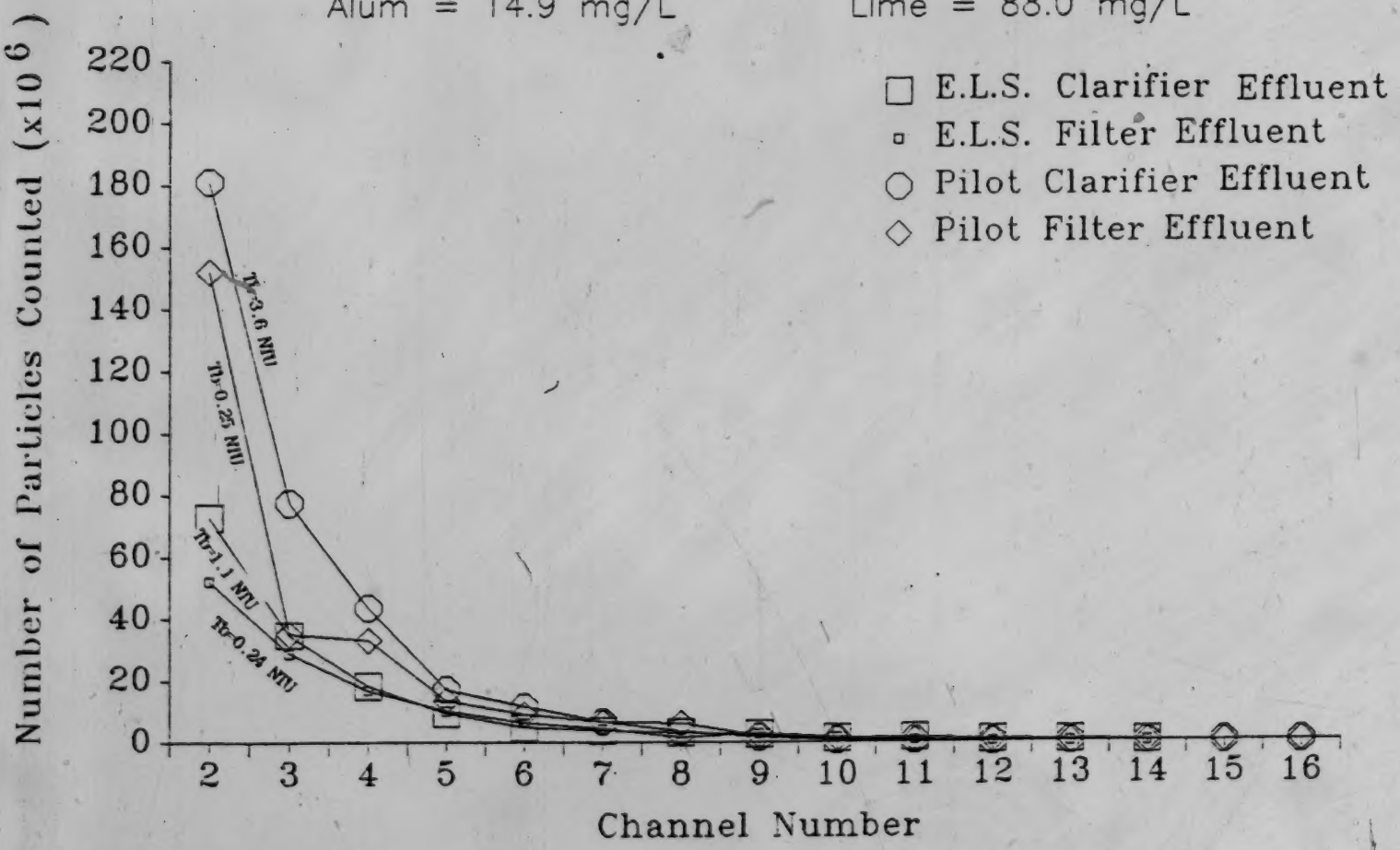
Figure 10 Particle Size Distribution
E. L. Smith Water Treatment Plant
Alum = 15.0 mg/L Lime = 90.0 mg/L



1. Giardia cyst size range is located between channels #3 - #6.

Figure 11 Particle Size Distribution
Run #4

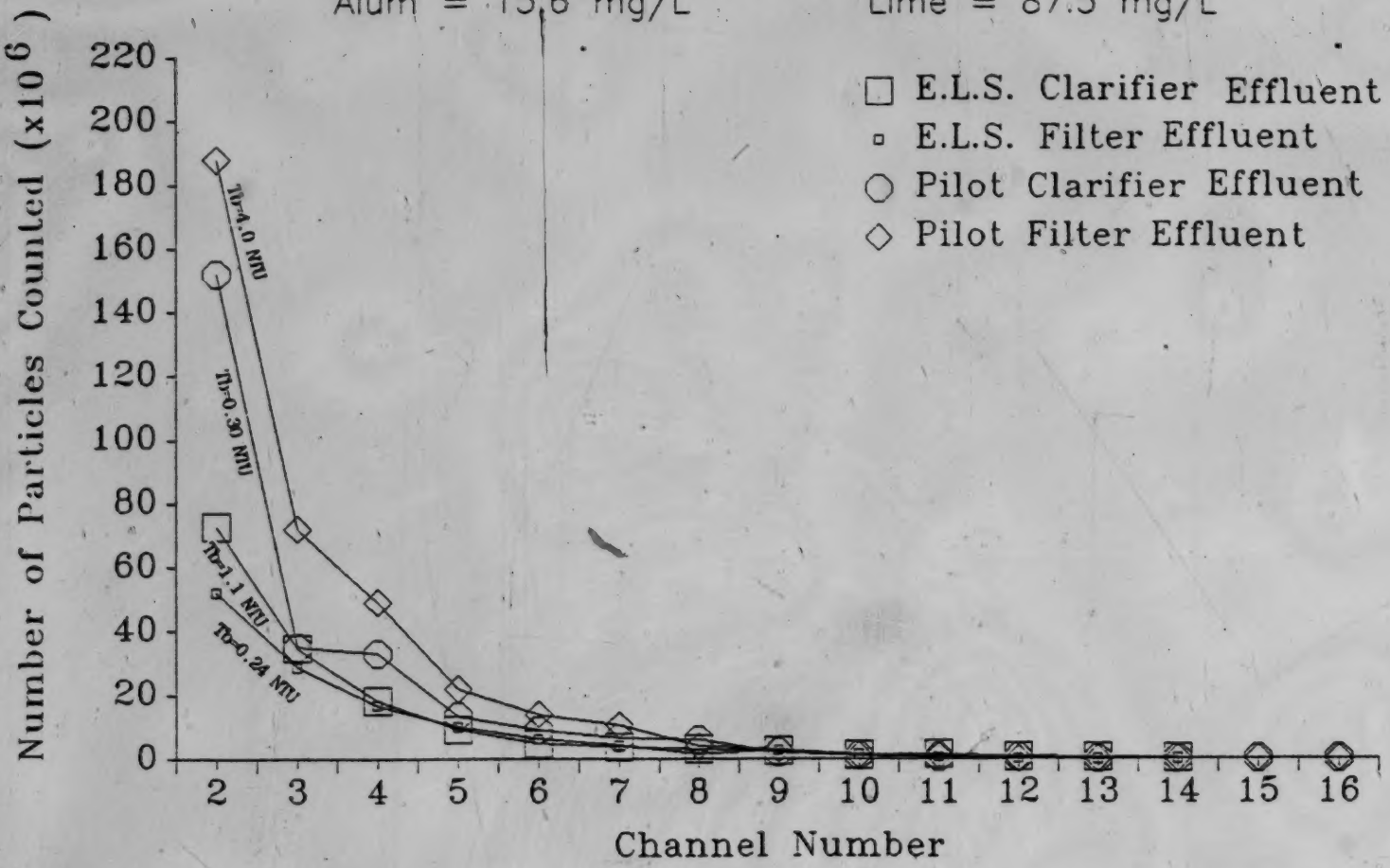
Alum = 14.9 mg/L Lime = 88.0 mg/L



1. Giardia cyst size range is located between channels #3 and #6.

Figure 12 Particle Size Distribution
Run #5

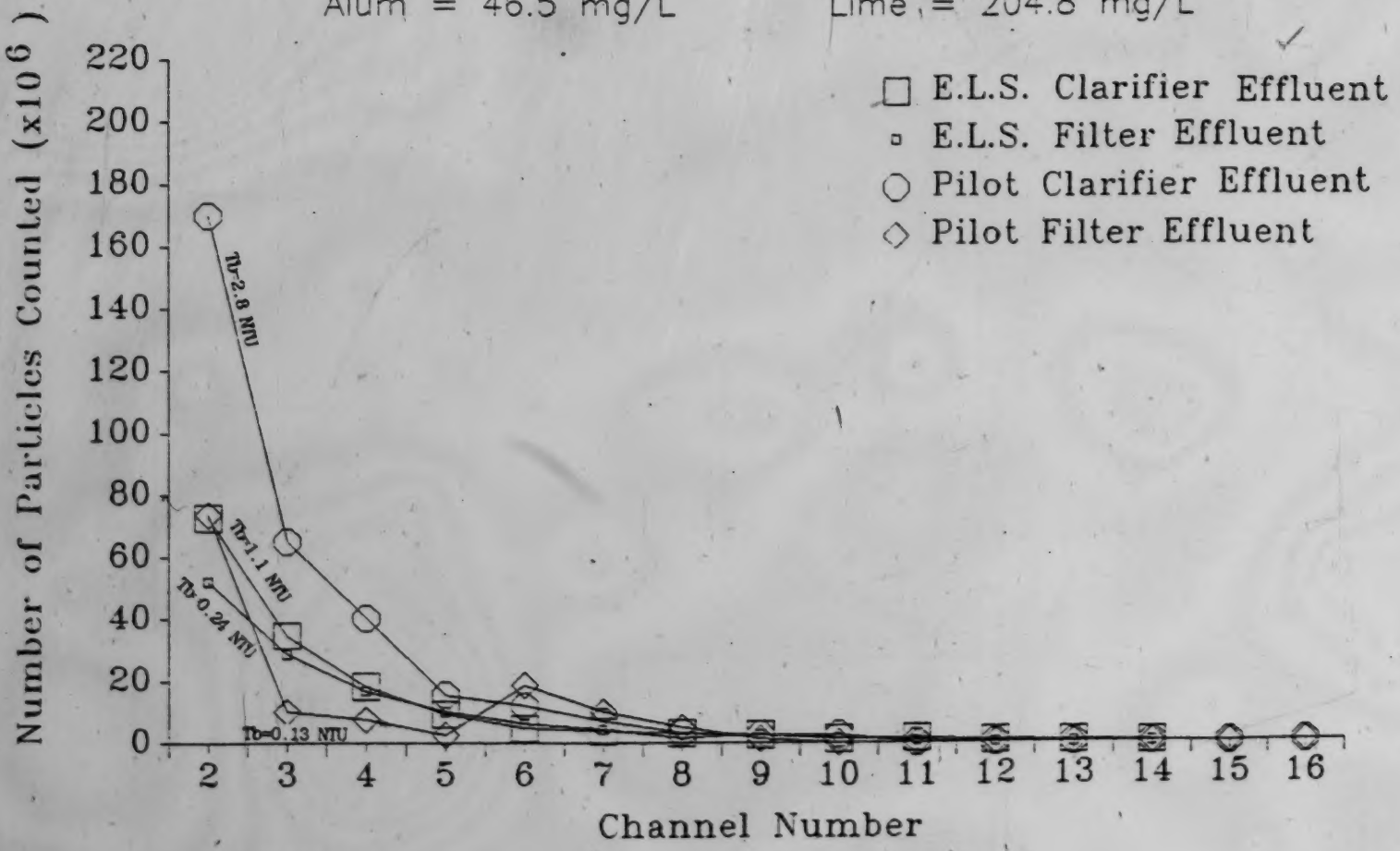
Alum = 15.6 mg/L Lime = 87.5 mg/L



1. Giardia cyst size range is located between channels #3 and #6.

Figure 13 Particle Size Distribution
Run #7

Alum = 46.5 mg/L Lime = 204.8 mg/L



1. Giardia cyst size range is located between channels #3 and #7.

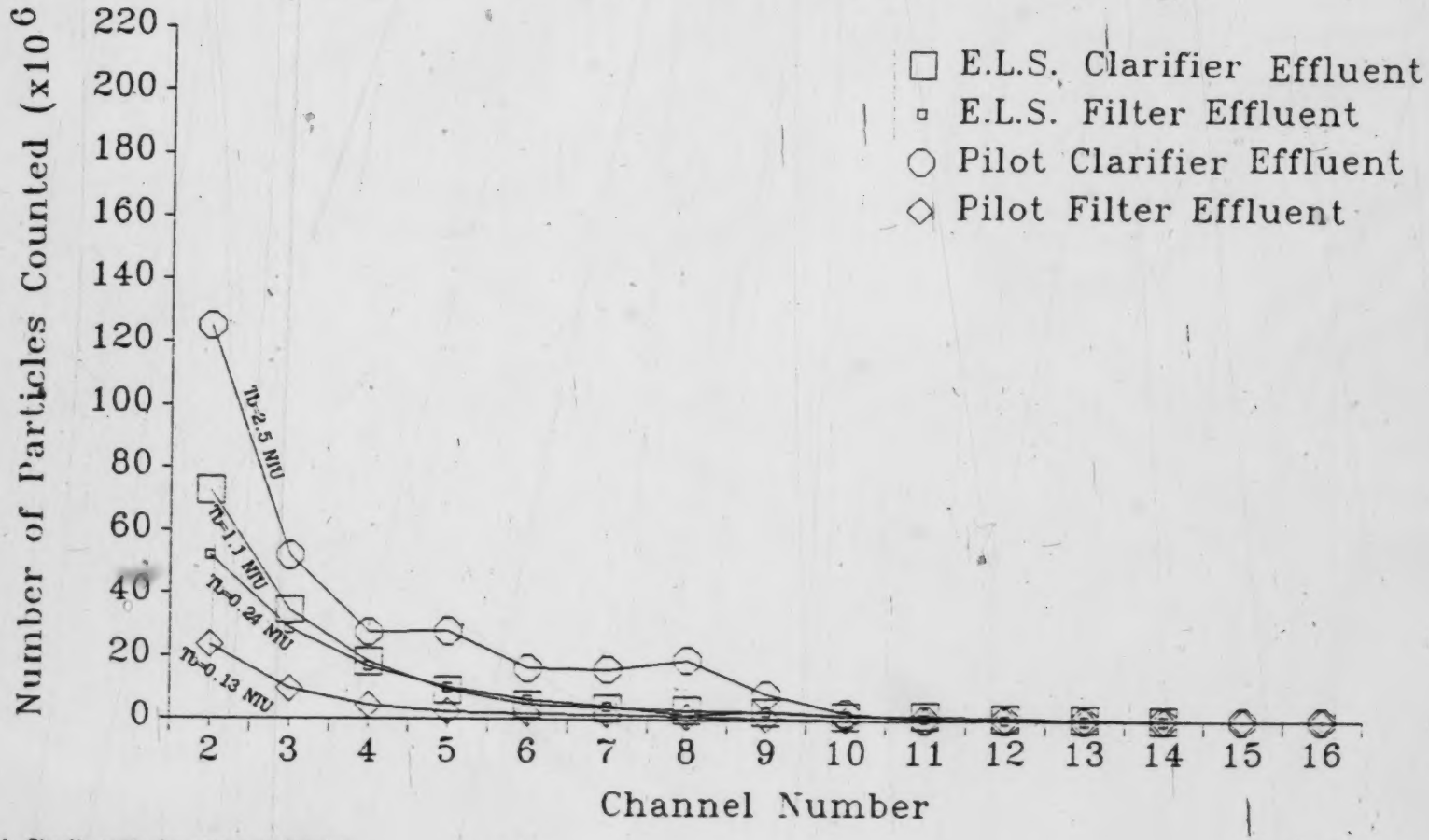
2 of/de 2

1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6

MICRO D

Figure 14 Particle Size Distribution
Run #8

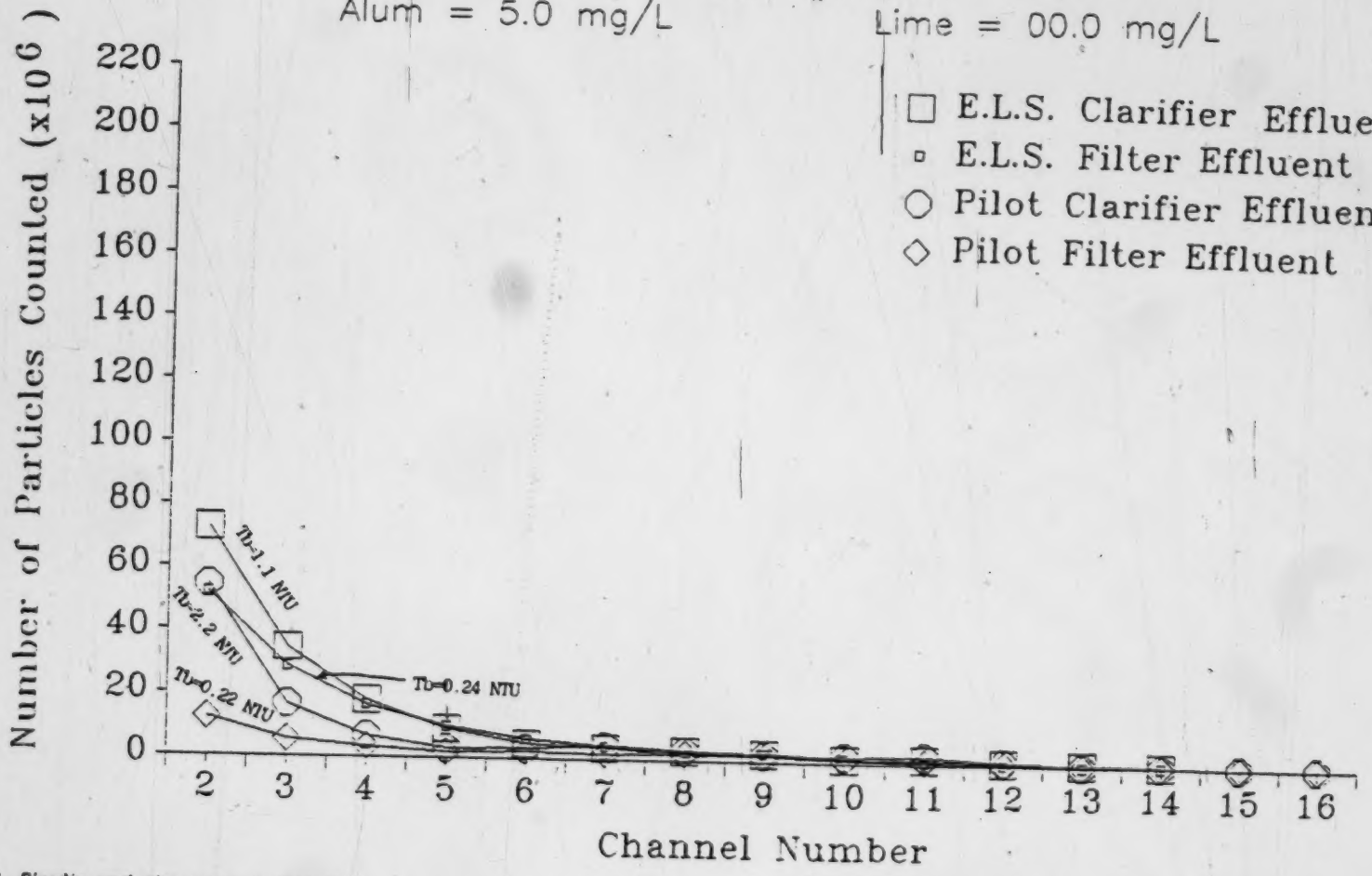
Alum = 5.1 mg/L Lime = 203.3 mg/L



1. Giardia cyst size range is located between channels #3 and #6.

Figure 15 Particle Size Distribution
Run #9

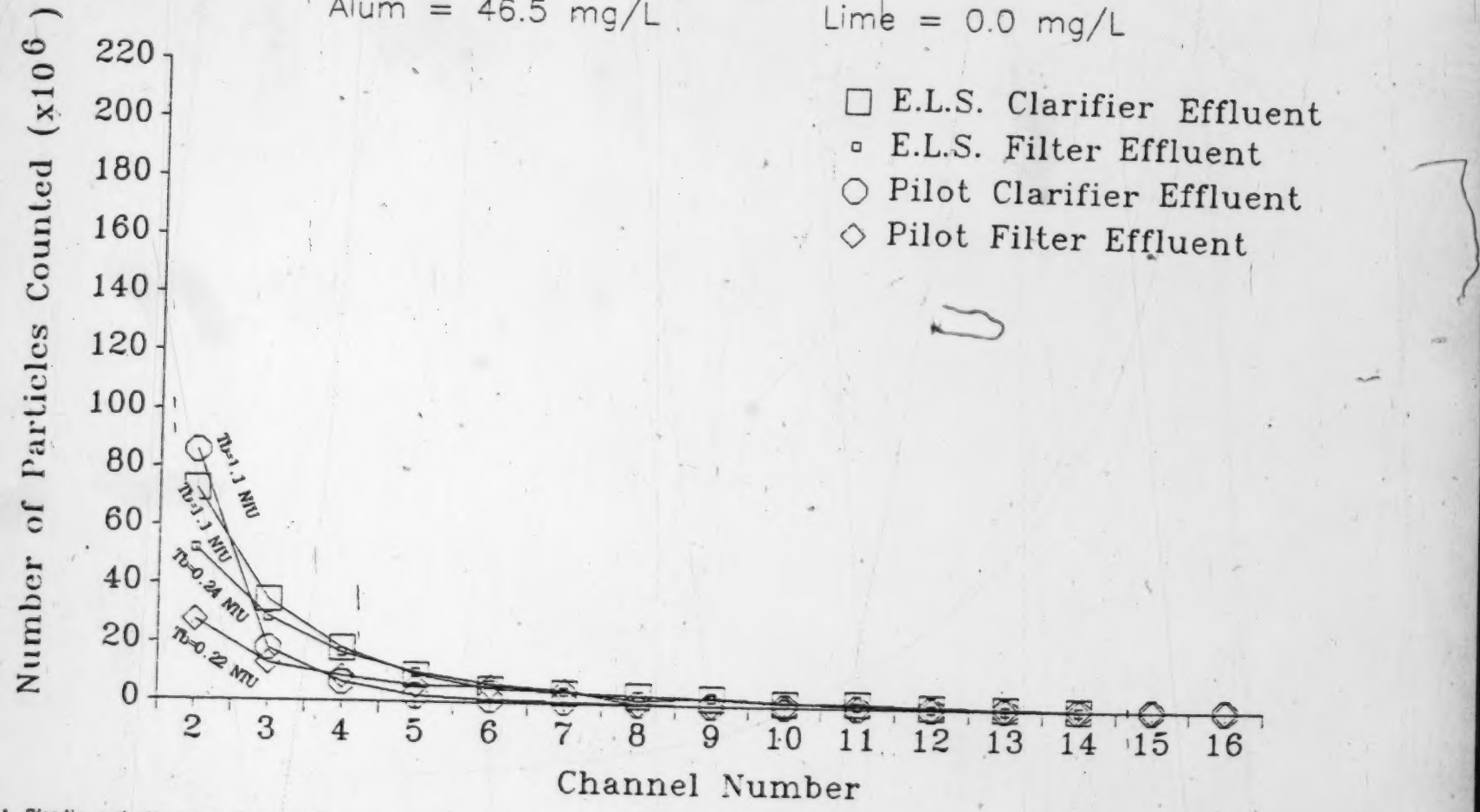
Alum = 5.0 mg/L Lime = 00.0 mg/L



1. Giardia cyst size range is located between channels #3 and #6.

Figure 16 Particle Size Distribution
Run #10

Alum = 46.5 mg/L Lime = 0.0 mg/L



1. Giardia cyst size range is located between channels #3 and #6.

In Figures 13 and 14, the pilot plant clarifier appears to be more efficient in particle removal than the full-scale operation. However, no lime was added during these runs so that this result more likely reflects a lower suspended solid content (due to the absence of lime floc) than more efficient clarifier behaviour. The pilot filter in both of these runs also appears to produce a higher quality effluent with respect to the quantity of particles. This may be a function of the lower quantity of particles in the influent or of better filter performance.

4.2.6 Particle Size Distribution Summary

Comparing Figures 15 and 16 with Figures 13 and 14 indicates that the large variation in the quantity of particles that are found in the clarifier effluent is directly related to the quantity of lime floc produced. In the absence of lime, the particle count in the pilot plant clarifier effluent is lower than what was found in the samples taken from the full-scale plant. On the other hand, when lime was used, the particle counts in the pilot plant samples were higher than those taken from the full-scale plant. Because the particle-size distribution in the clarifier is strongly related to the quantity and type of chemicals applied in pre-treatment, it alone cannot act as a reasonable indicator of sphere or cyst removals.

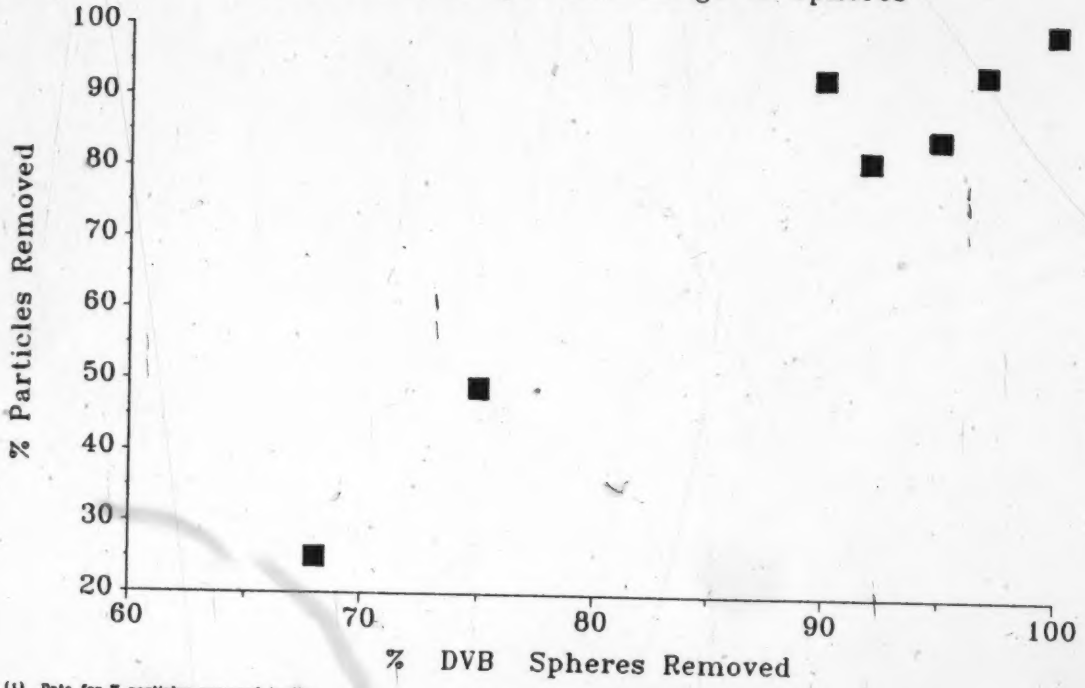
An examination of the particle-size distribution of the filtered water by itself shows a similar limitation in that the particle count in the effluent is a function of the

quality of the influent. Furthermore, observing very low numbers of particles in the Giardia size range does not necessarily guarantee low cyst concentrations. A more reliable indicator of the effectiveness of filtration would be to compare percent removals of particles in the Giardia cyst size range with percent removals of spheres.

4.2.7 Particle Removal vs Sphere Removal in the Filter

A comparison of the percentage of particles removed in the Giardia cyst size range (derived from the Coulter Counter data) versus sphere removals appears in Figure 17. The results show that the percent removals of latex spheres increase with the percent of particles removed in the cyst size range. When greater than ninety percent of the particulates are removed more than ninety percent of the spheres are also removed. Additional runs are needed to more clearly define this relationship but from this data it appears that measuring the percent removals of particles in a filter could be a useful diagnostic tool in predicting the removals of Giardia cysts.

Figure 17 % Removals in the Filter
Particles in Cyst Size Range vs Spheres



(1) Data for % particles removed in the cyst size range come from Coulter Counter results

4.2.8 Turbidity vs Sphere Removal in the Filter

The temptation to relate low cyst concentrations to low turbidity in the filter effluent is strong because turbidity measurements are performed routinely at most water treatment facilities. An effort has been made by some researchers to predict a minimum turbidity level in a properly operated water treatment plant below which the filtered water would be free of viable cysts.

The results from this experiment show no clear relationship between the lowest filter effluent turbidities and the lowest sphere concentrations. For instance, the data given in Table 10 shows that the lowest overall sphere count was observed in Run #4 when the effluent turbidity 3.0 hours into the run was 0.24 NTU. The next lowest sphere count was observed in Run #7 when the filter effluent turbidity 3.0 hours into the run was 0.13 NTU. The highest sphere count was found in Run #9 when the filter effluent turbidity was 0.22 NTU. Therefore, within the parameters of this experimentation the lowest turbidities are not an absolute indicator of the lowest sphere or cyst concentrations.

4.2.9. General Observations

In run #11 raw river water was processed through the pilot plant in the absence of either alum or lime. The clarifier data in Table 7 shows that this resulted in the lowest removals of latex spheres of all the runs. Removals in the filter were higher and were comparable with the low alum dose/zero lime dose results observed in Run #9.

Rendtdorff et al. (1964) has determined that it takes between one and ten cysts ingested orally to successfully infect an adult male. This very low threshold for infection places an enormous burden on a water treatment facility to remove or inactivate as many cysts as possible. One hundred percent removals would of course ensure safe drinking water but in actual practise 100 percent removal of cysts is never achieved. Determining what percentage of cyst removal is adequate is difficult because cyst concentrations in natural surface waters are largely unknown. There are two main reasons for this. Firstly, the state-of-the-art methods of cyst collection and identification are still inefficient and time consuming. Even if cysts are identified their detection often occurs after the infection has spread. Secondly, without knowing the source of cyst contamination an estimate of their actual concentrations in the raw water cannot be made. The best approach to the problem then is to optimize the performance of a water treatment plant in order to achieve the highest overall removals of cysts possible.

Table 10

Filter Effluent Turbidities and Overall Sphere Removals

Run #	Filter Effluent Turbidity (NTU)	Filter Effluent Sphere Count
4	0.24	132
5	0.25	116
7	0.13	128
8	0.13	198
9	0.22	1140
10	0.22	740

Overall cyst removals are a combination of clarifier and filter performance. In this study, the best removals of spheres in the clarifier were observed when lime softening was employed. The effect of using alum in combination with lime produced no significant reduction in sphere concentrations. In the filter, the best removals were observed when lime was not used concurrently with alum in pretreatment the pre-treatment step. Therefore the evidence suggests that a decoupling of the simultaneous addition of these two chemicals could lead to an overall improvement in sphere or cyst removals.

5. CONCLUSIONS

With respect to the laboratory technique:

(1) Polystyrene divinyl benzene latex spheres can act as a practical surrogate for Giardia lamblia cysts in a specific water treatment environment.

(2) A theoretical limit of 100% recovery of the spheres is possible with vacuum filtration that was developed. This alleviates the problem of filtering and centrifuging large sample volumes in order to collect enough spheres for enumeration.

(3) Epi-fluoescent microscopy is a useful tool for sphere enumeration because the spheres fluoresce in a characteristic manner. This allows them to be readily identified from the other particulates in the treated water.

(4) The possibility of using DVB styrene spheres as a substitute for measuring cyst removal efficiencies in a full-scale facility exists. Clearly, live cysts could not be used for such testing because of the danger they pose to public health.

With respect to the laboratory scale pilot plant testing:

(1) Spheres in the 12 µm to 14 µm range are more effectively filtered than spheres in the 6 µm to 8 µm size range. Therefore, larger cysts that are able to change shape due to

the flexibility of their cell walls have an increased potential to escape removal by filtration.

(2) Lowest effluent turbidity and lowest particle count in the Giardia cyst size range did not necessarily correlate with the lowest sphere concentrations. The measurement of turbidity however, in the absence of a better technique is still an useful parameter for gauging filter performance if its limitations are recognized.

(3) A correlation was demonstrated between the percent of particles removed in the Giardia cyst size range and percent spheres removed and this can provide a useful diagnostic tool for measuring filter performance.

(4) Clarifier performance in the removal of the latex spheres improves significantly with the addition of calcium hydroxide. However addition of calcium hydroxide appeared to reduce the effectiveness of alum in the removal of spheres in the filter. The evidence suggests that overall plant performance can be improved if the softening and coagulation steps are separated since better alum complexing of the spheres would result at a lower pH.

6. RECOMMENDATIONS

(1) The possibility of using a Giardia cyst surrogate to measure the performance of a full-scale plant with respect to cyst removals should be further investigated. An improvement to the recovery and enumeration technique could be made by the use of specially coated fluorescent DVB spheres which fluoresce very brightly under UV light. These spheres are more easily identified under a lower power of magnification and would significantly reduce the time needed for counting.

(2) The interactive effects on sphere (and cyst) removals of using both alum and lime simultaneously in pre-treatment should be further investigated. Evidence from this study indicates that concurrent lime softening and alum coagulation is detrimental to the ability of the filter to remove Giardia lamblia sized spheres.

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Appendix I

Summary of Latex Sphere Counts During Experimentation

1. Abbreviations

(a) Sample Ports: B1 and B2 refer to the raw water storage barrels

: 3 refers to the post clarifier location

: 4 refers to the post filter location

: " ' " refers to the count after correction has been made for the dilution factor and/or the background count

2. Sample Calculations

(a) Dilution: Liquid alum flow rate = 46.5 ml/min

Liquid lime flow rate = 82.5 ml/min

Raw water flow rate = 822.2 ml/min

$$\text{Dilution ratio} = \frac{(822.2 + 46.5 + 82.5)}{822.2}$$

$$= 1.16$$

(b) Background Count Calculations

Prior to dosing the raw water with latex spheres, samples were taken and analyzed for particles that could be confused with latex spheres based on size, shape, and fluorescent characteristics. The following, using Run #4 data shows how this count was obtained and distributed downstream.

Raw water background = 1 per 10.00 ml.

= 100 per 1000 ml.

Post clarifier background = Raw water background x (avg. post clarifier count / avg. raw water count)

= 100 x 132/2500

= 5 per 1000 ml. or

= 1 per 250.0 ml.

Post filter background = Post clarifier background x (avg. post filter count / avg. post clarifier count)

= 5 x 4/132 = 2 in 1000 ml

(c) Redistribution (or B1') Calculations

(Count in size range - (Background count x Count in size range/ Total count)) / Dilution ratio

(i.e.) 6m-8m = (1 - (1 x 1/32)) /1.16 = 0.84

= or 1

(i.e.) 8m-10m = (13 - (1 x 13/32)) /1.16 = 10.85

= or 11

(i.e) 10m-12m = (13 - (1 x 13/32)) /1.16 = 10.85

= or 11

(i.e) 12m-14m = (5 - (1 x 5/32)) /1.16 = 4.16

= or 4

(d) Calculation of the % of Latex Spheres Removed

Post Clarifier (total) = (1 - Avg. total clarifier count/ Avg. total raw water count) x 100%

= (1 - 198 / 5800) x %100

= 98.29%.

Post Filter (total) = (1 - Avg. total filter count/ Avg. total clarifier count) x 100%
= (1 - 9 / 198) x %100
= 90.91%.

Overall (total) = (1 - Avg. total filter count/ Avg. raw water count) x %100
= (1 - 9 / 5800) x %100
= 99.84%.

(e) The values given inside the brackets represent the distribution of particles that was expected based on the manufacturer's specification which is presented in Appendix III. The actual distribution differs in the raw water count due to the pipetting technique. Further on downwstream the differences are due to the mechanisms of removal. The bracketed data is presented for informational purposes only and was not included in any other calculations.

Run #4

Table No. A1
Alum = 14.9 mg/L Lime = 88.0 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
B1	10.00	1(2)[1]	13(14)[1]	13(15)[1]	5(2)[1]	32[1]
B1	10.00	4(1)	11(13)	9(13)	4(1)	28
B1	10.00	5(2)	10(13)	10(14)	5(1)	30
B2	10.00	6(2)	10(13)	9(14)	5(1)	30
B2	10.00	5(2)	11(14)	10(14)	5(1)	31
B2	10.00	4(2)	12(14)	11(14)	4(1)	31
Dilution = 1.16[1]		Background Count = 1 per 10.00 ml.[1]				
B1'	10.00	1(1)	11(12)	11(12)	4(1)	28
B1'	10.00	4(1)	9(10)	7(11)	5(1)	24
B1'	10.00	5(1)	8(11)	8(11)	5(1)	24
B2'	10.00	6(1)	8(11)	7(11)	5(1)	24
B2'	10.00	5(1)	9(12)	8(12)	5(1)	26
B2'	10.00	4(1)	10(12)	9(12)	4(1)	26
Avg.	10.00	4(1)	9(11)	8(12)	5(1)	25
Avg.	1000	400	900	800	500	2500[1]
3	250.0	10(2)	11(14)	7(15)	4(1)	32
3	250.0	12(2)	15(16)	5(16)	3(1)	35
3	250.0	12(2)	11(16)	8(16)	4(1)	35
		Background Count = 1 per 250.0 ml.[1]				
3'	250.0	10(2)	10(14)	7(14)	4(1)	31
3'	250.0	12(2)	11(16)	8(16)	4(1)	33
3'	250.0	12(2)	10(15)	8(16)	4(1)	34
Avg.	250.0	11(2)	11(15)	6(15)	4(1)	33
Avg.	1000	44	44	24	16	132[1]
4	1000	13(2)	16(21)	13(23)	5(2)	45
4	1000	7(2)	15(18)	14(19)	5(2)	41
4	1000	~~3(1)~~	~~6(8)~~	~~5(8)~~	~~3(1)~~	~~17~~
		Background Count = 2 per 1000 ml.[1]				
4'	1000	13(2)	16(21)	13(22)	5(2)	45
4'	1000	7(2)	15(18)	14(19)	5(2)	41
4'	1000	~~3(1)~~	~~5(7)~~	~~4(7)~~	~~3(1)~~	~~15~~
Avg.	1000	15(2)	15(19)	13(21)	5(<1)	42[1]
% of Latex Spheres Removed						
Post Clarifier		89.00	95.11	92.50	96.80	94.72[1]
Post Filter		65.91	65.91	78.33	68.75	68.18[1]
Overall		96.25	98.33	98.38	99.00	98.32[1]

Table No. A2

Run #5 Alum = 15.6 mg/L Lime = 89.9 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
R1	10.00	2(2)	11(14)	11(15)	8(1)	32
R1	10.00	5(2)	11(14)	10(15)	5(1)	31
R1	10.00	5(2)	10(13)	9(14)	6(1)	30
R2	10.00	7(1)	8(13)	8(13)	5(1)	28
R2	10.00	7(2)	13(16)	12(17)	4(1)	36
R2	10.00	6(2)	12(15)	10(15)	5(1)	33
Dilution = 1.16		Background Count = 1 per 10.00 ml.				
R1'	10.00	2(1)	9(12)	9(12)	8(1)	28
R1'	10.00	5(1)	9(12)	8(12)	5(1)	27
R1'	10.00	5(1)	8(11)	7(11)	6(1)	26
R2'	10.00	7(1)	6(10)	6(11)	5(1)	24
R2'	10.00	7(2)	10(13)	9(14)	4(1)	30
R2'	10.00	6(1)	10(12)	7(13)	5(1)	28
Avg.	10.00	5(1)	9(12)	8(12)	5(1)	27
Avg.	1000	500	900	800	500	2700
3	250.0	4(2)	10(13)	11(14)	5(1)	30
3	250.0	8(2)	9(13)	12(14)	1(1)	30
3	250.0	5(2)	11(12)	11(12)	1(1)	27
		Background Count = 1 per 250.0 ml.				
3'	250.0	4(2)	10(13)	11(13)	5(1)	30
3'	250.0	8(2)	9(13)	12(13)	1(1)	30
3'	250.0	5(1)	11(12)	11(12)	1(1)	27
Avg.	250.0	6(2)	10(13)	11(13)	2(1)	29
Avg.	1000	24	40	44	8	116

Table No. A2 (continued)

Run #5 Alum = 15.6 mg/L Lime = 89.9 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
4	1000	10(2)	14(15)	8(16)	2(1)	34
4	1000	11(2)	13(14)	5(14)	2(1)	31
4	1000	9(2)	15(15)	7(16)	3(1)	34
4	1000	11(2)	11(13)	7(14)	1(1)	27
4	1000	8(1)	10(10)	3(10)	1(1)	22
4	1000	8(1)	12(12)	6(12)	1(1)	27
4	1000	7(1)	8(10)	6(10)	1(1)	22
Background Count = 1 per 1000 ml.						
4'	1000	10(2)	14(15)	8(15)	2(1)	34
4'	1000	11(2)	13(13)	5(14)	2(1)	31
4'	1000	9(2)	15(15)	7(15)	3(1)	34
4'	1000	11(2)	11(13)	7(13)	1(1)	30
4'	1000	8(1)	10(9)	3(10)	1(1)	22
4'	1000	8(1)	12(12)	6(12)	1(1)	27
4'	1000	7(1)	8(9)	6(10)	1(1)	22
Avg.	1000	9(2)	12(12)	6(13)	2(1)	29
% of Latex Spheres Removed						
Post Clarifier		95.20	95.58	94.50	98.67	95.69
Post Filter		62.50	70.00	86.36	75.00	75.34
Overall		98.20	98.60	99.25	99.67	98.94

Table No. A3

Run #6 — Alum = 15.6 mg/L Lime = 87.5 mg/L

Sample Port	Sample (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
B1	10.00	3(1)	8(9)	6(9)	2(1)	19
B1	10.00	2(1)	9(9)	10(10)	0(1)	21
B1	10.00	3(1)	8(10)	10(11)	2(1)	23
B2	10.00	2(1)	6(8)	6(8)	4(1)	18
B3	10.00	3(1)	10(11)	10(11)	1(1)	24
B3	10.00	2(1)	8(8)	7(9)	2(1)	19
B3	10.00	3(1)	9(9)	7(10)	2(1)	21
Dilution = 1.14		Background Count = 1 per 10.00 ml.				
B1'	10.00	3(1)	7(7)	4(7)	2(1)	16
B1'	10.00	2(1)	7(8)	8(8)	0(1)	17
B1'	10.00	3(1)	6(9)	8(9)	2(1)	19
B2'	10.00	2(1)	5(7)	5(7)	4(1)	16
B3'	10.00	2(1)	8(9)	8(9)	1(1)	19
B3'	10.00	2(1)	7(7)	5(7)	1(1)	15
B3'	10.00	3(1)	7(8)	5(8)	1(1)	16
Avg.	10.00	2(1)	7(8)	8(8)	2(1)	18
Avg.	1000	200	700	800	200	1800
3	250.0	5(1)	12(12)	9(12)	1(1)	27
3	250.0	6(2)	11(13)	10(13)	2(1)	29
		Background Count = 2 per 250.0 ml.				
3'	250.0	5(1)	11(11)	8(12)	1(1)	26
3'	250.0	6(1)	10(12)	9(13)	2(1)	29
Avg.	250.0	6(1)	10(12)	9(13)	2(1)	27
Avg.	1000	24	40	36	8	108

Table No. A3 (cont.)

Run #6 Alum = 15.6 mg/L Lime = 87.5 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
4	500	2(0)	3(3)	1(3)	0(0)	6
4	500	0(0)	2(1)	0(1)	1(0)	3
4	500	1(0)	2(2)	1(2)	0(0)	4
4	500	2(0)	4(3)	0(3)	0(0)	6
4	500	1(0)	0(1)	2(1)	0(0)	3
4	500	1(0)	3(2)	1(2)	0(0)	5
4	1000	4(1)	6(5)	2(6)	0(0)	12
4	1000	5(1)	5(5)	2(6)	0(0)	12
4	1000	3(1)	6(5)	2(5)	0(0)	11
Background Count = 1 per 1000 ml.						
4'	500	2(0)	3(2)	1(3)	0(0)	6
4'	500	0(0)	2(1)	0(1)	1(0)	3
4'	500	1(0)	2(2)	1(2)	0(0)	4
4'	500	2(0)	4(2)	0(3)	0(0)	6
4'	500	1(0)	0(1)	2(1)	0(0)	3
4'	500	1(0)	3(2)	1(2)	0(0)	5
4'	1000	4(1)	6(5)	2(5)	0(0)	12
4'	1000	5(1)	5(5)	2(5)	0(0)	12
4'	1000	3(1)	6(4)	2(5)	0(0)	11
Avg.	1000	3(0)	5(4)	2(4)	0(1)	10
% of Latex Spheres Removed						
Post Clarifier		88.00	93.71	95.50	96.00	93.76
Post Filter		87.50	88.64	94.44	100.00	90.84
Overall		98.50	99.29	99.75	100.00	99.41

Table No. A4

Run #7 Alum = 46.5 mg/L Lime = 204.8 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
B1	10.00	10(3)	25(29)	22(30)	7(3)	64
B1	10.00	10(4)	25(31)	24(31)	9(3)	68
B1	10.00	9(3)	22(28)	23(29)	8(2)	62
B1	10.00	7(3)	24(26)	20(26)	6(2)	60
B2	10.00	6(3)	23(25)	18(25)	8(2)	55
B2	10.00	8(3)	24(27)	20(27)	7(2)	59
B2	10.00	6(3)	22(28)	27(29)	7(2)	62
Dilution = 1.25		Background Count = 1 per 10.00 ml.				
B1'	10.00	9(3)	19(22)	16(23)	6(2)	50
B1'	10.00	9(3)	18(24)	17(25)	8(2)	52
B1'	10.00	8(3)	16(22)	17(22)	7(2)	48
B1'	10.00	6(2)	19(21)	15(22)	5(2)	45
B2'	10.00	5(2)	18(19)	12(20)	8(2)	43
B2'	10.00	7(2)	18(21)	14(21)	7(2)	46
B2'	10.00	5(3)	16(22)	21(22)	6(2)	48
Avg.	10.00	7(3)	18(22)	16(22)	7(2)	47
Avg.	1000	700	1800	1600	700	4700
3	250.0	5(2)	14(13)	10(14)	2(1)	31
3	250.0	2(2)	18(15)	11(15)	2(1)	33
3	250.0	4(2)	14(14)	13(14)	2(1)	33
3	250.0	4(2)	13(14)	13(15)	2(1)	32
		Background Count = 1 per 250.0 ml.				
3'	250.0	5(2)	14(14)	10(14)	2(1)	31
3'	250.0	2(2)	18(15)	11(15)	2(1)	33
3'	250.0	4(2)	14(14)	13(15)	2(1)	33
3'	250.0	4(2)	13(14)	13(15)	2(1)	32
Avg.	250.0	4(2)	15(14)	12(15)	2(1)	32
Avg.	1000	8	60	48	8	128

Table No. A4 (cont.)

Run #7 Alum = 46.5 mg/L Lime = 204.8 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
4	500.0	3(0)	2(4)	2(4)	1(0)	8
4	500.0	2(0)	4(4)	2(4)	0(0)	8
4	500.0	1(0)	3(3)	1(3)	1(0)	6
4	500.0	3(0)	2(3)	1(3)	0(0)	6
4	500.0	1(0)	3(2)	1(2)	0(0)	5
4	1000	2(1)	5(4)	2(5)	1(0)	10
4	1000	2(1)	6(4)	1(5)	0(0)	10
4	1000	3(1)	6(5)	2(6)	1(0)	12
Background Count = 0 per 1000 ml.						
4'		(all same as above)				
Avg.	1000	3(0)	6(6)	2(6)	1(1)	12
% of Latex Spheres Removed						
Post Clarifier		95.87	96.67	97.00	98.86	97.26
Post Filter		70.00	90.00	95.83	87.50	90.18
Overall		99.57	99.67	99.88	99.86	99.73

Table No. A5

Run #8 Alum = 5.1 mg/L Lime = 203.3 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
B1	10.00	8(4)	31(36)	34(37)	7(3)	80
B1	10.00	6(4)	27(31)	32(32)	5(3)	70
B1	10.00	5(4)	31(32)	31(33)	5(3)	72
B2	10.00	6(4)	28(33)	32(33)	8(3)	74
B2	10.00	7(4)	28(33)	32(34)	7(3)	73
Dilution = 1.25		Background Count = 1 per 10.00 ml.				
B1'	10.00	7(3)	23(28)	26(29)	6(2)	62
B1'	10.00	5(3)	20(25)	25(25)	4(2)	54
B1'	10.00	4(3)	24(25)	24(25)	4(2)	56
B2'	10.00	5(3)	21(26)	25(26)	7(2)	58
B2'	10.00	6(3)	21(26)	25(26)	6(2)	58
Avg.	10.00	5(3)	22(26)	25(27)	5(2)	58
Avg.	1000	500	2200	2500	500	5800
3	500.0	9(5)	44(44)	37(45)	8(4)	98
3	500.0	10(5)	46(44)	38(38)	4(4)	98
3	500.0	12(5)	43(46)	44(47)	3(4)	102
3	500.0	12(5)	46(44)	36(45)	3(4)	97
		Background Count = 1 per 500.0 ml.				
3'	500.0	9(5)	44(44)	37(45)	8(4)	98
3'	500.0	10(5)	46(44)	38(38)	4(4)	98
3'	500.0	12(5)	43(46)	44(47)	3(4)	102
3'	500.0	12(5)	46(44)	36(45)	3(4)	97
Avg.	500.0	11(5)	45(44)	39(44)	5(4)	99
Avg.	1000	22	90	78	10	198
4	500.0	3(0)	1(2)	0(2)	0(0)	4
4	500.0	2(0)	3(2)	0(2)	0(0)	5
4	500.0	2(0)	2(2)	0(2)	0(0)	4
4	1000	2(0)	3(4)	3(4)	0(0)	8
4	1000	3(0)	4(4)	1(4)	0(0)	8
4	1000	2(0)	5(4)	3(4)	0(0)	10
		Background Count = 0 per 1000 ml.				
4'		(all same as above)				
Avg.	1000	4(0)	4(4)	1(4)	0(0)	9
		% of Latex Spheres Removed				
Post Clarifier		95.60	95.91	96.88	98.00	98.29
Post Filter		81.82	95.56	100.00	100.00	95.62
Overall		99.20	99.82	100.00	100.00	99.85

Table No. A6

Run #9 Alum = 0.0 mg/L Lime = 0.0 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
B1	10.00	5(3)	25(28)	28(29)	4(2)	62
B1	10.00	5(3)	19(27)	29(28)	7(2)	61
B1	10.00	11(3)	21(28)	27(29)	3(2)	62
B2	10.00	7(3)	22(27)	27(27)	3(2)	62
B2	10.00	7(3)	27(29)	28(30)	3(3)	65
Dilution = 1.03		Background Count = 1 per 10.00 ml.				
B1'	10.00	5(3)	24(27)	27(27)	4(2)	60
B1'	10.00	5(3)	18(26)	28(27)	7(2)	58
B1'	10.00	11(3)	20(27)	26(28)	3(2)	60
B2'	10.00	7(3)	21(25)	26(26)	3(2)	59
B2'	10.00	7(3)	26(28)	27(29)	3(3)	63
Avg.	10.00	7(3)	22(27)	27(27)	4(2)	60
Avg.	1000	700	2200	2700	400	6000
3	500.0	30(20)	166(173)	172(178)	18(15)	386
3	500.0	28(20)	162(168)	167(173)	17(15)	374
3	500.0	41(20)	146(172)	179(177)	18(15)	384
3	500.0	38(21)	156(183)	185(182)	17(15)	396
3	100.0	11(4)	32(34)	29(35)	3(3)	75
3	100.0	16(4)	23(30)	25(31)	3(3)	67
		Background Count = 6 per 500.0 ml.				
3'	500.0	30(20)	163(170)	169(175)	18(15)	380
3'	500.0	28(19)	159(165)	164(169)	17(14)	368
3'	500.0	41(20)	143(169)	176(174)	18(15)	378
3'	500.0	38(20)	153(174)	182(179)	17(15)	390
3'	100.0	11(4)	31(33)	28(34)	3(3)	73
3'	100.0	16(3)	22(29)	24(30)	3(3)	65
Avg.	1000	90(38)	290(329)	320(339)	30(30)	740

Table No. A6 (cont.)

Run #9 Alum = 46.2 mg/L Lime = 0.0 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
4	500.0	7(2)	14(13)	8(14)	1(1)	30
4	500.0	5(1)	14(12)	6(12)	2(1)	27
4	1000	12(3)	29(26)	16(27)	2(2)	59
4	1000	10(3)	28(27)	20(28)	3(2)	61
Background Count = 1 per 1000 ml.						
4'	500.0	7(2)	14(13)	8(14)	1(1)	30
4'	500.0	5(1)	14(12)	6(12)	2(1)	27
4'	1000	12(3)	29(26)	16(27)	2(2)	59
4'	1000	10(3)	28(27)	19(27)	3(2)	60
Avg.	1000	12(3)	28(27)	16(27)	4(2)	58
% of Latex Spheres Removed						
Post Clarifier		87.14	89.09	88.15	92.50	87.74
Post Filter		86.67	88.33	95.00	86.67	92.09
Overall		98.29	98.73	99.41	99.00	99.03

Run #10

Table No. A7

Alum = 46.2 mg/L Lime = 0.0 Mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
B1	10.00	9(6)	41(50)	52(51)	9(4)	110
B1	10.00	9(5)	38(41)	45(42)	8(4)	92
B1	10.00	8(5)	41(44)	44(46)	6(4)	99
B1	10.00	7(5)	39(43)	42(44)	7(4)	95
B2	10.00	6(6)	43(49)	50(50)	10(4)	109
B2	10.00	7(6)	49(49)	49(50)	8(4)	109
B2	10.00	6(6)	45(49)	51(51)	8(4)	110
Dilution = 1.07			Background Count = 1 per 10.00 ml.			
B1'	10.00	9(5)	37(46)	48(47)	9(4)	103
B1'	10.00	9(4)	27(38)	42(39)	8(3)	86
B1'	10.00	8(5)	38(41)	41(42)	6(4)	93
B1'	10.00	7(5)	36(39)	39(40)	7(3)	89
B2'	10.00	6(5)	39(45)	46(46)	10(4)	101
B2'	10.00	7(5)	45(45)	40(46)	8(4)	100
B2'	10.00	6(5)	41(46)	48(47)	8(4)	103
Avg.	10.00	7(5)	38(43)	48(48)	8(4)	96
Avg.	1000	700	3800	4800	800	9600
3	100.0	8(5)	36(42)	46(43)	3(4)	93
3	100.0	8(6)	42(47)	53(49)	3(4)	106
3	100.0	9(5)	42(49)	40(45)	6(4)	97
3	250.0	15(17)	140(142)	148(146)	13(12)	316
3	250.0	22(18)	145(154)	160(158)	16(13)	343
3	250.0	20(17)	132(148)	164(152)	12(13)	329
			Background Count = 3 per 250.0 ml.			
3'	100.0	8(5)	35(41)	45(42)	3(4)	91
3'	100.0	8(6)	41(47)	52(48)	3(4)	104
3'	100.0	9(5)	41(48)	39(44)	6(4)	95
3'	250.0	15(16)	139(140)	147(146)	13(12)	314
3'	250.0	22(18)	144(152)	159(157)	16(13)	341
3'	250.0	20(17)	131(146)	163(150)	12(13)	326
Avg.	1000	80(61)	471(519)	539(522)	47(46)	1140

Table No. A7 (cont.)

Run #10 Alum = 5.0 mg/L Lime = 0.0 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
4	500.0	4(1)	6(6)	3(6)	0(1)	13
4	500.0	1(1)	6(6)	6(6)	1(1)	14
4	500.0	5(1)	6(6)	3(6)	0(1)	14
4	500.0	3(1)	4(5)	4(5)	0(0)	11
4	500.0	2(1)	6(6)	3(6)	1(1)	13
4	500.0	4(1)	6(6)	2(6)	1(1)	13
4	1000	2(1)	12(10)	8(10)	0(1)	22
4	1000	4(1)	13(11)	6(11)	1(1)	24
Background Count = 0 per 1000 ml.						
4'		(all same as above)				
Avg.	1000	6(1)	12(11)	7(11)	1(1)	25
% of Latex Spheres Removed						
Post Clarifier		88.57	87.61	88.77	94.13	88.12
Post Filter		92.50	97.45	98.70	97.87	97.97
Overall		99.14	99.68	99.85	99.98	99.74

Table No. A8

Run #11 (Blank) Alum = 0.0 mg/L Lime = 0.0 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
B1	10.00	6(3)	21(22)	19(23)	3(2)	49
B1	10.00	5(3)	23(24)	23(24)	1(2)	53
B2	10.00	6(3)	20(23)	20(23)	5(2)	51
B2	10.00	7(3)	19(22)	21(23)	3(2)	50
No Dilution		Background Count = 1 per 10.00 ml.				
B1'	10.00	6(3)	20(21)	19(23)	3(2)	48
B1'	10.00	5(3)	22(23)	23(24)	1(2)	52
B2'	10.00	6(3)	19(22)	20(23)	5(2)	50
B2'	10.00	7(3)	18(21)	21(23)	3(2)	49
Avg.	10.00	6(3)	20(22)	21(23)	3(2)	50
Avg.	1000	600	2000	2100	300	5000
3	25.00	4(2)	18(16)	10(16)	3(1)	35
3	25.00	7(2)	12(15)	11(16)	4(1)	34
3	25.00	4(2)	17(14)	9(15)	1(1)	32
3	25.00	4(2)	21(17)	12(17)	0(1)	37
		Background Count = 1 per 25.00 ml.				
3'	25.00	4(2)	17(15)	10(16)	3(1)	34
3'	25.00	7(2)	11(14)	10(16)	4(1)	33
3'	25.00	4(2)	16(13)	8(14)	1(1)	31
3'	25.00	4(2)	20(16)	11(16)	0(1)	36
Avg.	25.00	5(2)	16(15)	10(16)	2(1)	34
Avg.	1000	200	640	440	80	3400

Table No. A8 (cont.)

Run #11 Alum = 0.0 mg/L Lime = 0.0 mg/L

Sample Port	Sample Size (ml)	Number of Latex Spheres Counted				
		6μ-8μ	8μ-10μ	10μ-12μ	12μ-14μ	Total
4	250.0	6(2)	17(15)	11(16)	0(1)	34
4	250.0	4(2)	14(14)	12(14)	1(1)	31
4	250.0	3(2)	16(13)	9(14)	2(1)	30
4	250.0	4(2)	17(13)	9(14)	0(1)	30
4	250.0	3(1)	17(13)	5(13)	1(1)	27
4	250.0	3(1)	15(12)	7(12)	1(1)	26
4	250.0	7(2)	14(13)	6(13)	2(1)	29
4	1000	10(6)	47(49)	49(51)	4(4)	110
4	1000	11(6)	51(48)	45(50)	1(4)	108
4	1000	9(6)	47(47)	47(48)	4(4)	105
Background Count = 2 per 250.0 ml.						
4'	250.0	6(2)	16(14)	9(15)	0(1)	31
4'	250.0	4(2)	13(13)	11(13)	1(1)	29
4'	250.0	3(2)	15(12)	8(13)	2(1)	28
4'	250.0	4(2)	16(12)	8(13)	0(1)	28
4'	250.0	3(1)	16(11)	4(11)	1(1)	24
4'	250.0	3(1)	14(11)	6(11)	1(1)	24
4'	250.0	7(2)	13(12)	5(12)	2(1)	27
4	1000	10(5)	43(45)	45(47)	4(4)	102
4	1000	11(5)	47(44)	41(46)	4(4)	103
4	1000	9(5)	43(43)	43(44)	2(4)	97
Avg.	1000	16(6)	55(47)	32(49)	4(4)	107
% of Latex Spheres Removed						
Post Clarifier		66.67	68.00	80.95	73.33	73.20
Post Filter		92.50	91.41	91.75	95.00	92.16
Overall		97.80	97.25	98.43	98.67	97.87

Appendix II

Pilot Plant Operation

The following is a step-by-step guide to the procedure used during a typical run. In order to maximize the number of runs an effort was made to conserve sample water. Keeping the water cold was a priority. During experimentation all raw river water was stored in 220 litre barrels inside a walk-in refrigerator so as to reduce the possibility of biological growth and to facilitate further cooling before each run. The two clarifiers and the alum and lime tanks were also stored empty in the refrigerator between runs.

1. Run Preparation

(i) The quantity of aluminum sulphate and calcium hydroxide (based on the dosing rate) that was required for the next run was calculated. The chemicals were weighed out and then stored with sufficient distilled make-up water overnight in the refrigerator (@5^{0} C.).

(ii) A barrel of tap water was also stored overnight in the refrigerator.

(iii) Two 10.00 ml. volumes were pipetted from the latex sphere stock solution (conc. = approx 50,000 per ml.) into two 220 litre raw water barrels. This yielded a raw water latex sphere count of approx. 2300 in each barrel.

(iv) The spiked raw water was vigorously mixed with a mechanical stirrer for 20 minutes. At least three 10.00 ml.

samples were collected from each barrel for fluorescent count analysis. Then, 110 litres was siphoned from each barrel into a third and mixed. The two remaining halves were combined.

2. Run Procedure

(i) The tap water was removed from the refrigerator and positioned near the cooling tank. Regulated positive air pressure was used to force the contents of the barrel into the insulated cooling tank at a controlled rate (see Figure A1). An air line was connected to the apparatus and the air pressure was turned up to 69 kN/m^2. The cooling tank was filled to approx. 3/4 full.

(ii) The air was shut-off to stop filling the cooling tank and the electric cooler was then turned on. The temperature of the tap water in the cooling tank was reduced to 3^oC. or 4^oC. Ice was seen to form on the copper cooling coil.

(iii) The insulated clarifier tanks that had been stored in the refrigerator were installed and the piping was connected.

(iv) The centrifugal raw water pump was started and the upper reservoir was charged by drawing tap water from the cooling tank. The air supply was turned on in order to replenish the tap water in the cooling tank which had been drawn off. The air pressure was regulated in order to maintain a constant suction-side head level. in the cooling tank. The detention time in the cooling tank was 30 minutes

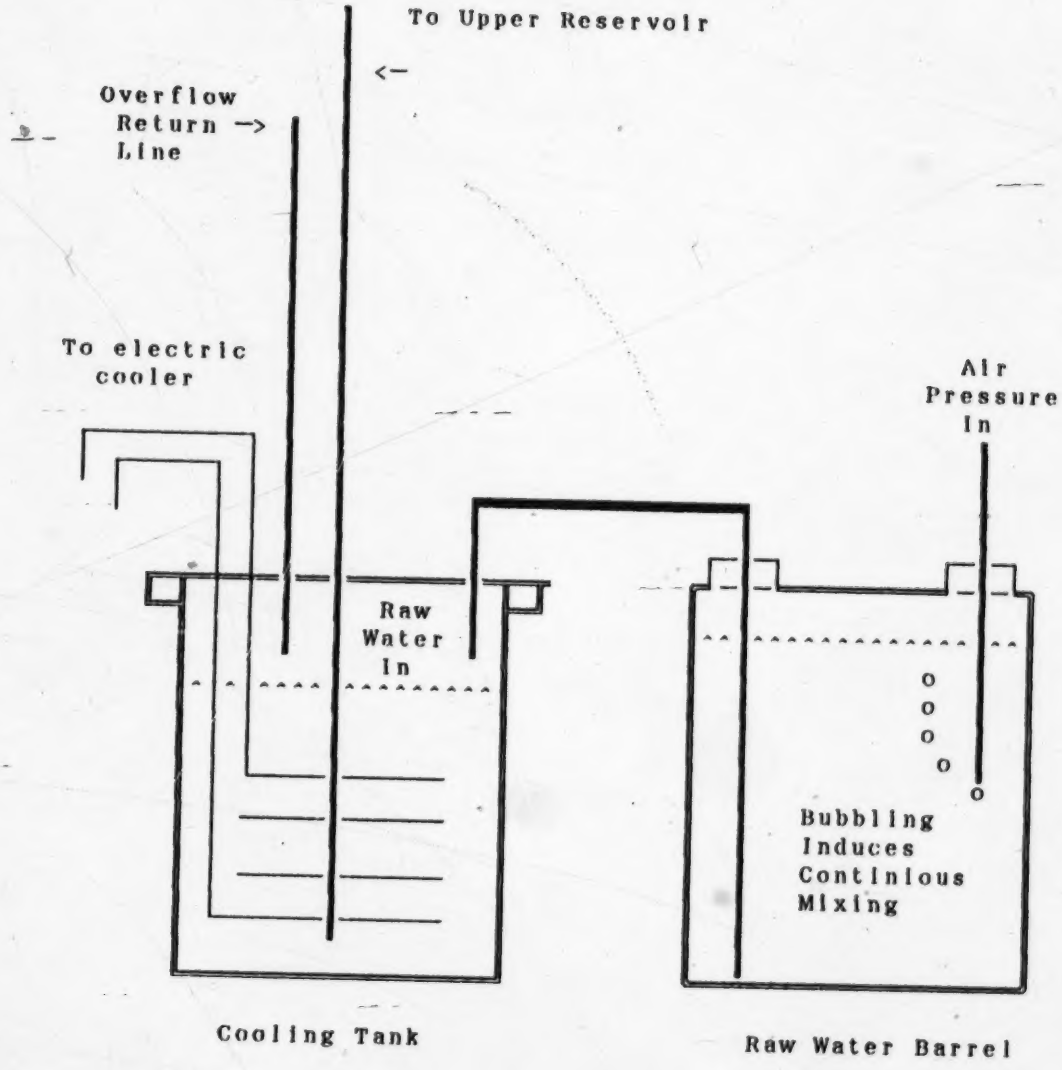


Figure No. A1 Transfer of Raw Water From Barrel to Cooling Tank

or greater.

(v) When the upper reservoir filled, any overflow recycled back into the cooling tank. At this point the valve at the base of the reservoir was opened in order to fill the other downstream units (approx 1.5 to 2.0 hrs.). Clarifier #2 effluent was routed back into the cooling tank to complete the cooling circuit. Recycling was continued until the clarifier effluent dropped to 3^{o} to 4^{o}.

(vi) Meanwhile, the experimental raw water flow rate (RWFR) was set. The discharge of the pump was large enough so as to exceed the downstream requirement of the plant. Any extra flow was wasted to the drain. The upper reservoir acted as an hydraulic device that produced constant head when overflowing and as a result delivered a non-fluctuating flow to the system. Total plant flow rate (TFR) was ultimately based on the desired filter loading rate. The calculation used to obtain the raw water flow rate was a function of the alum flow rate (AFR) and the lime flow rate (LFR); both of which varied according to the concentration of alum and lime in solution and the dosages needed. The equations used were:

(a) $RWFR = TFR - AFR - LFR$

where,

$AFR = TFR \times ALUM_{dose} / [ALUM_{tank}]$

$LFR = TFR \times LIME_{dose} / [LIME_{tank}$

(b) Considerations in solving the formulae were:

; TFR was a function of the filter loading

rate x 1.2

: [$ALUM_{tank}$] was high enough so that refilling during the run was avoided.

: [$LIME_{tank}$] was such that the lime tank was refilled every two hours thus minimizing the oxidation of the lime in solution.

: The dilution ratio (TFR) / (RWFR) was as low as possible.

(c) The actual RWFR was measured by the bucket-and-stopwatch method at the clarifier #2 effluent location and was adjusted by a valve on the upper reservoir effluent line. All clarifier overflow valves were kept closed during RWFR calibration.

(vii) Once the temperature and raw water flow rate conditions had been met, the raw water pump, the air pressure, and drain the tap water from the cooling tank were all shut-off. A barrel of river water was taken from the walk-in refrigerator, connected to the positive air pressure apparatus. When the air pressure was re-applied the cooling tank was refilled with sample water. The raw water pump was re-started and the system was charged with with sample water. Initially, all the effluent from clarifier #2 was wasted to the drain. During the run, a constant water level was maintained in the cooling tank.

(viii) Using the cooled distilled make-up water and the previously weighed chemicals a batch of dissolved alum and lime was prepared. These solutions were used for dosing the raw water. The chemical storage tanks were filled and

connected to the raw water stream. The chemical feed pumps were then started and dosing was initiated. AFR and LFR were controlled by calibrated variable speed pumps and drives and were monitored with calibrated flowmeters.

(ix) The rapid mixer paddle and the flocculator stirrers were switched on.

(x) Using the bucket-and-stopwatch method the TFR was checked at the clarifier #2 effluent location.

(xi) The overflow valves on each of the clarifier were opened.

(xii) The flow was re-directed to the filter when the tap water was flushed out of the system (i.e. the sum of the theoretical detention times of each of the units multiplied by 1.5). Alternatively, since the addition of lime significantly changes the pH, flow to the filter could be initiated when the pH had stabilized at the new higher level.

(xiii) The filter column was filled to the overflow port and then the filter flow control valve was gently opened. Using the filter flowmeter to gauge flow rate, the control valve was adjusted so as to acheive the required filter loading rate. An overflow rate of approx 10% was maintained.

(xiv) After the first 10 minutes the filter control valve was re-adjusted to achieve the desired flowrate.

(xv) Carbon dioxide for recarbonation was introduced through the backwash water overflow line. With the backwash overflow control valve off, the CO_2 cylinder pressure valve was opened. Then the backwash overflow control

valve was slowly opened and carbon dioxide was allowed to bubble through the water in the upper portion of the column. Gas flowrate was adjusted as necessary for proper pH values.

(xvi) At this point, continious operation had been established. The next barrel was connected to the system when the first became exhausted.

3. Shutdown Procedure

When the run was completed:

(i) The carbon dioxide gas was shut-off and the backwash overflow control valve was closed.

(ii) The cooling system was switched-off (first the electric refrigeration unit then the ethylene glycol pump).

(iii) Next, the raw water pump was switched off.

(iv) The flocculator and rapid mix stirrers were stopped.

(v) The alum and lime chemical feed pumps were switched-off. The dosing tanks were emptied and refilled with tap water. The tanks and the pumps were re-connected and both lines were flushed with clean water.

(vi) The clarifier and cooling tank bottom drain valves were opened.

4. Backwashing

(i) If filtered water was collected for backwashing then the raw water pump was connected to the backwash water feed

line.

(ii) If tap water is used for backwashing then the backwash water feed line was connected directly to the tap.

(iii) The water in the column was drained to a level 150 mm above the media. The air-line was connected to the air diffusion unit at the bottom of the column and using the flowmeter, air scoured at a rate of 1.21 m^3/ m^2 for four to five minutes.

(iii) The pump was started or the tap water valve was opened.

(iv) The backwash water flow control valve located at the base of the flowmeter was immediately opened and the flow was slowly increased until the desired flowrate or bed expansion had been reached (i.e 490 to 730 LPM/m^2). Backwashing was continued for a minimum of 10 minutes or until the backwash water became visually clean.

(v) The backwash control valve was then slowly closed.

(vi) The pump was switched off or the tap water valve was closed.

(vii) The raw water pump was reconnected to the cooling tank in preparation for the next run.

Appendix III

Miscellaneous Data

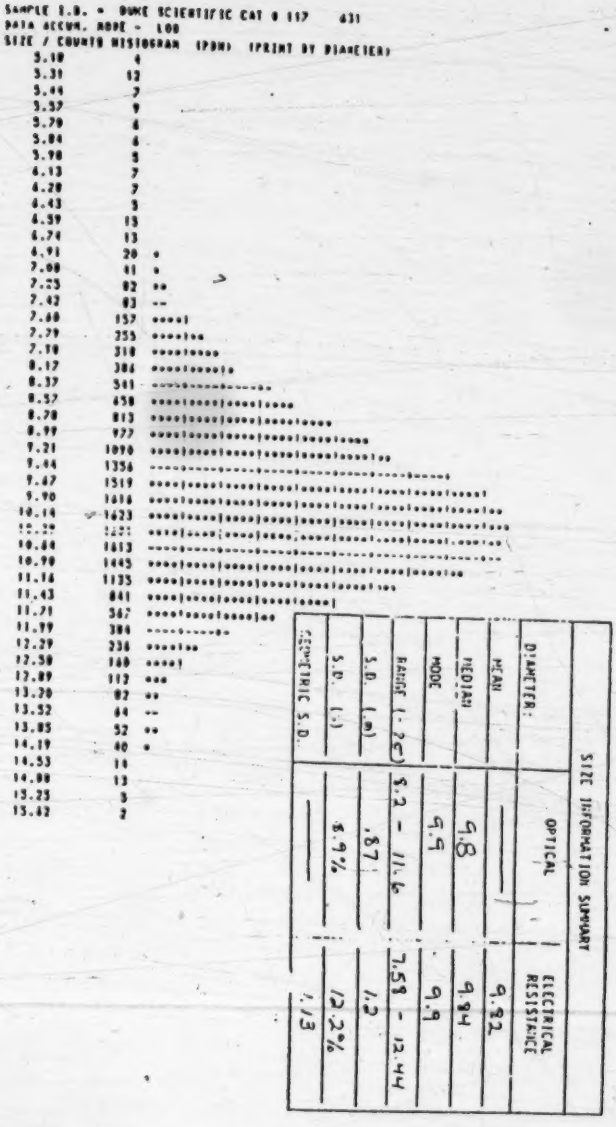
(a) Table 10A: Zeta Potential Measurements of the 10mm Polystyrene Divinyl Benzene latex Spheres.

nn (b) Figure A2: Manufacturer's Specification for Size Distribution of the Latex Spheres.

(c) Table 11A: Channel # and Corresponding Size Range for the 280mm Aperture.

Table 18A.
Zeta Potential Measurements of the Polystyrene DVB Latex Spheres

Sample #	Temp °C	µmhos x10³	K	Volts	µA x10³	pH	# of Meas.	Avg. Mobility @ 8x/Div	Zeta Potential (millivolts)
1	26	2.2	65	200	7.0	3.3	3	4.13	-18.7
2	27	2.2	65	200	7.0	4.9	3	2.56	-31.5
3	27	2.2	65	200	7.0	5.9	3	4.16	-19.5
4	27	2.3	65	200	7.2	6.7	3	4.59	-17.8
5	27	2.4	65	200	7.4	8.0	3	4.84	-17.0
6	27	2.4	65	200	7.5	10.0	3	5.07	-16.0



SAMPLE I.D. = DUKE SCIENTIFIC CAT # 117 431
DATA ACCUM. MODE = LOG
SIZE / COUNTS HISTOGRAM (PDH) (PRINT BY DIAMETER)

5.10	4	
5.31	12	
5.44	7	
5.57	9	
5.70	6	
5.84	6	
5.98	9	
6.13	7	
6.28	7	
6.43	5	
6.59	15	
6.74	13	
6.91	20	*
7.08	41	*
7.25	82	**
7.42	83	**
7.60	157	*****
7.79	255	*******
7.98	318	*********
8.17	384	**********|
8.37	541	----------------
8.57	658	**********|**********
8.78	813	**********|**********|**********
8.99	977	**********|**********|**********|**********
9.21	1090	**********|**********|**********|**********|**
9.44	1356	----------|----------|----------|----------|------
9.67	1519	**********|**********|**********|**********|**********|
9.90	1616	**********|**********|**********|**********|**********|**********
10.14	1623	**********|**********|**********|**********|**********|**********
10.39	1551	**********|**********|**********|**********|**********|**********
10.64	1613	----------|----------|----------|----------|----------
10.90	1495	**********|**********|**********|**********|**********
11.16	1135	**********|**********|**********|**********|**********|**
11.43	841	**********|**********|**********|**********
11.71	567	**********|**********|**********|
11.99	384	----------
12.29	236	*********
12.58	148	****|
12.89	113	***
13.20	82	**
13.52	64	*
13.85	52	**
14.19	40	*
14.53	14	
14.88	13	
15.25	5	
15.62	2	

PRODUCT IDENTIFICATION

117	LOT # 5261	
SN # 41410	SIZE: 5.0 um	
PREPARED BY: BL	DATE: 3/18/83	CERTIFIED BY: [illegible] DATE: 3/11/83

SIZE INFORMATION SUMMARY

DIAMETER:	OPTICAL	ELECTRICAL RESISTANCE
MEAN	———	9.92
MEDIAN	9.8	9.84
MODE	9.9	9.9
RANGE (1-2σ)	8.2 - 11.6	7.53 - 12.44
S.D. (σ)	.87	1.2
S.D. (σ)	8.9%	12.2%
GEOMETRIC S.D.	———	1.13

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Palo Alto California 94306
(415) 328-2400

Figure A2 Manufacturer's Specifications for Latex Spheres

Table 11A

Channel # and Size Range for 280µm Aperture

Channel Number	Particle Diameter (µm)
2	5.Ø4
3	6.35
4	8.ØØ
5	1Ø.Ø8
6	12.7
7	16.Ø
8	2Ø.2
9	25.4
1Ø	32.Ø
11	4Ø.3
12	5Ø.8
13	64.Ø
14	8Ø.6
15	1Ø1.6
16	----